# Measuring new particle masses at the LHC

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In collaboration with:

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arXiv:1008.1813 [hep-ph]
arXiv:1010.3962 [hep-ph]

4/11/2010 DAMTP

# Contents

- Introduction
- Methods of new particle mass measurement

  -- kinematic variables

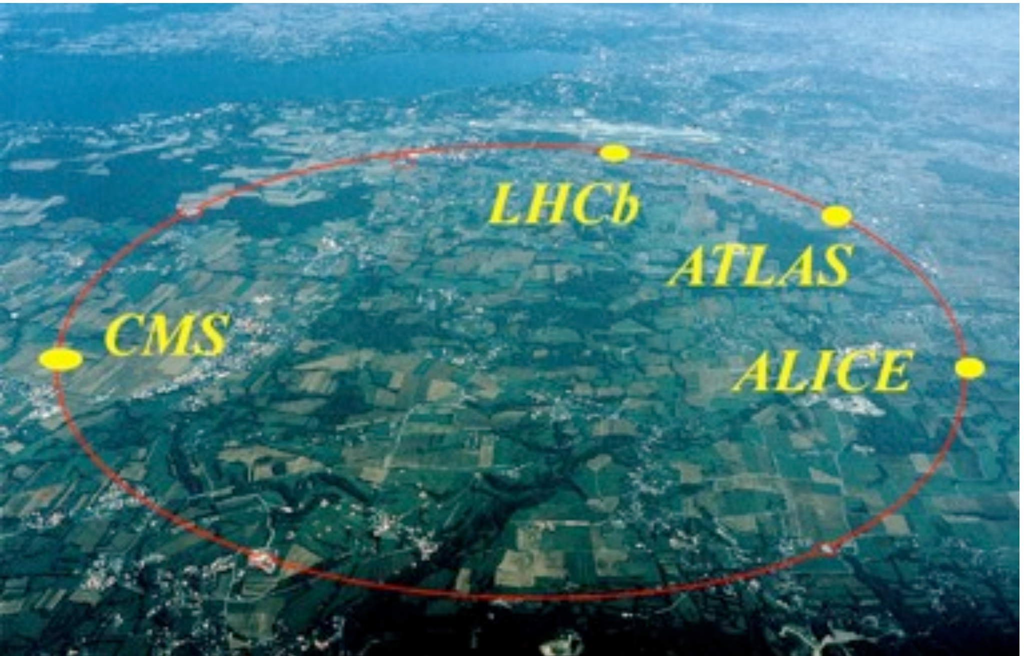
  -- event by event constraints

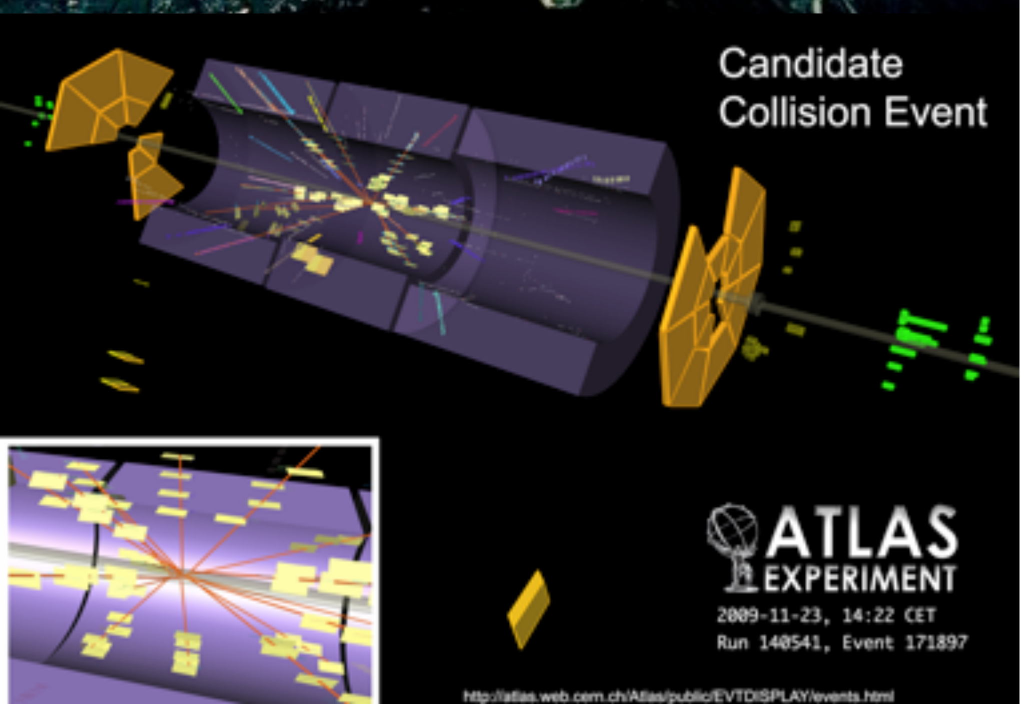
- For the early stage of the LHC

  ( low energy 7 TeV,  low luminosity 1fb$^{-1}$ )

- Summary

# Large Hadron Collider




23/11/2009: first collision at 0.9 TeV

30/3/2011: 7 TeV collision started

Now: integrated lumi. $\sim$50 $pb^{-1}$

**searching for new physics**

# Invisible particle

❖ New physics lies on TeV scale may contain invisible particles.

- Cosmological observation indicates there exists non-SM particle in the Universe, which must be stable and invisible (called Dark Matter).

- Many extension of the standard model (SM) introduce a new stable particle as a consequence of new symmetry (parity), and it is usually invisible (neural under strong and E.M. interactions).

MSSM: R-parity
UED: KK-parity
⋮

$BSM_i(-) \not\longrightarrow SM(+), SM(+)$

$BSM_i(-) \longrightarrow SM(+), BSM_f(-)$

Lightest BSM particle is stable.

neutralino, (sneutrino), gravitino in MSSM

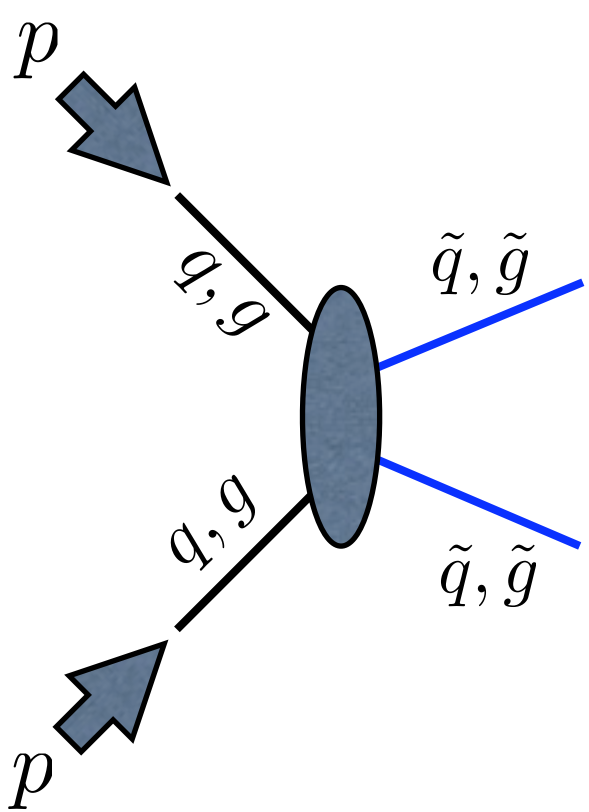
KK-photon, KK-neutrino in UED

# Production and Decay

- New (coloured) particles are produced **in pair** due to parity.

$$\text{SM}(+), \text{SM}(+) \not\longrightarrow \text{BSM}(-), \text{SM}(+)$$

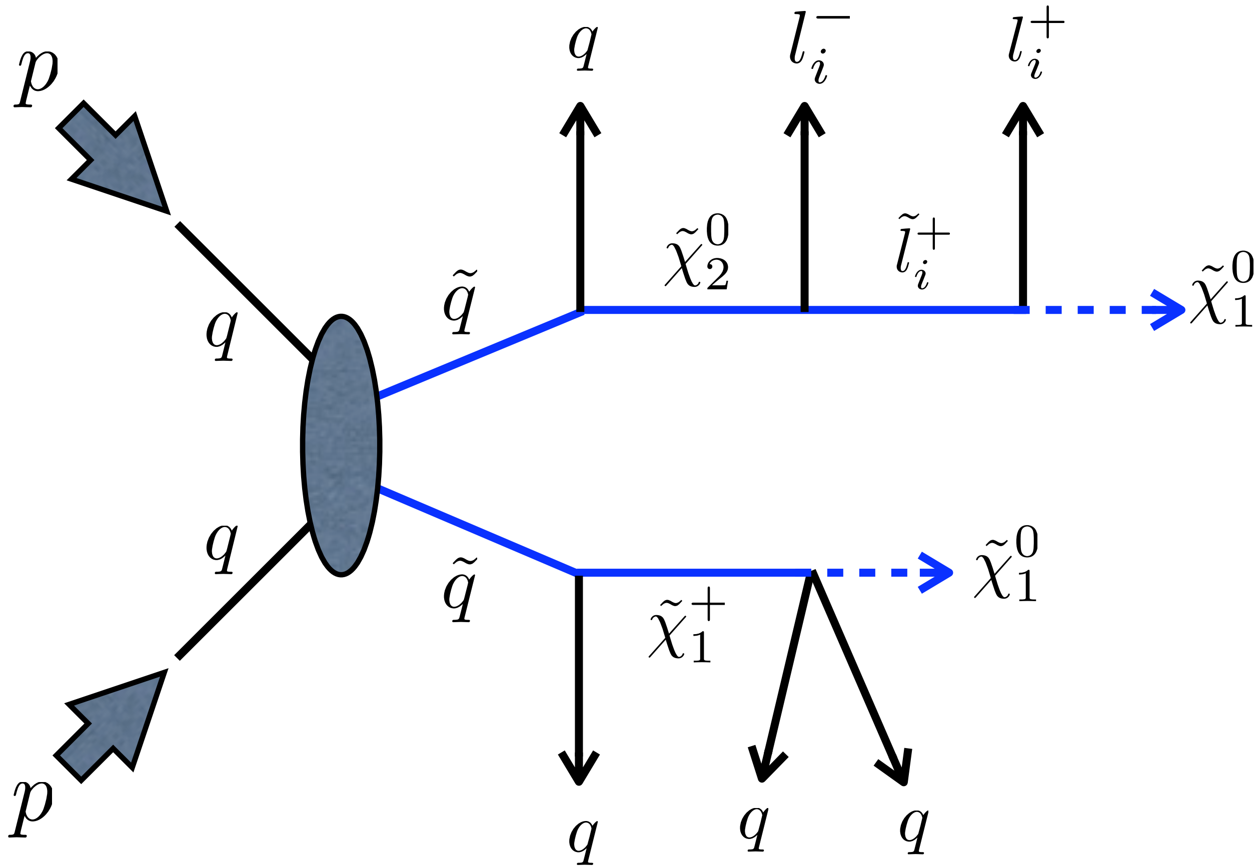
$$\text{SM}(+), \text{SM}(+) \longrightarrow \text{BSM}(-), \text{BSM}(-)$$



# Production and Decay

- New (coloured) particles are produced **in pair** due to parity.

- Because of the strong interaction, coloured BSM particles are more likely produced. They decay towards the colourless invisible particles producing many SM particles, leaving **many jets (and leptons)** and at least **two invisible particles**.



# New Physics Signature

New physics events may contain **many jets (and leptons)** and **large missing energy** carried by two invisible particles.

## ❖ Advantage

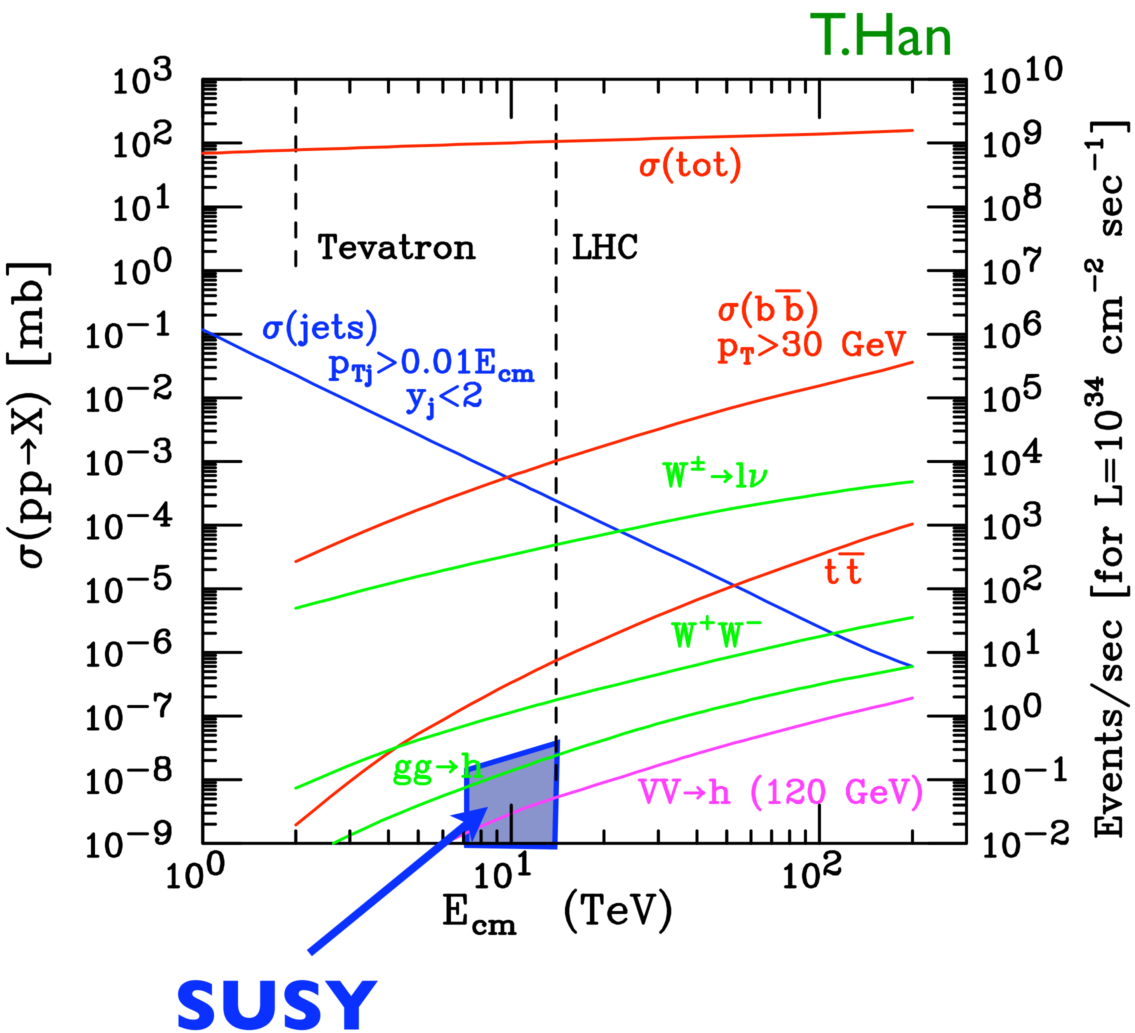
-- can distinguish new physics signature from huge SMBG

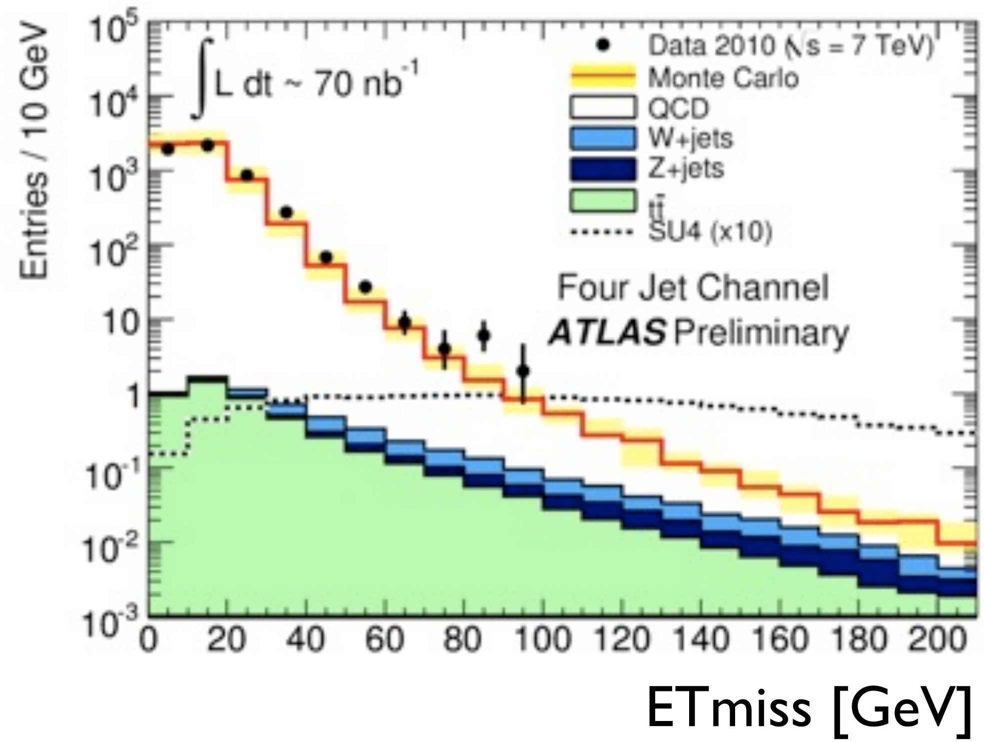
## ❖ Disadvantages

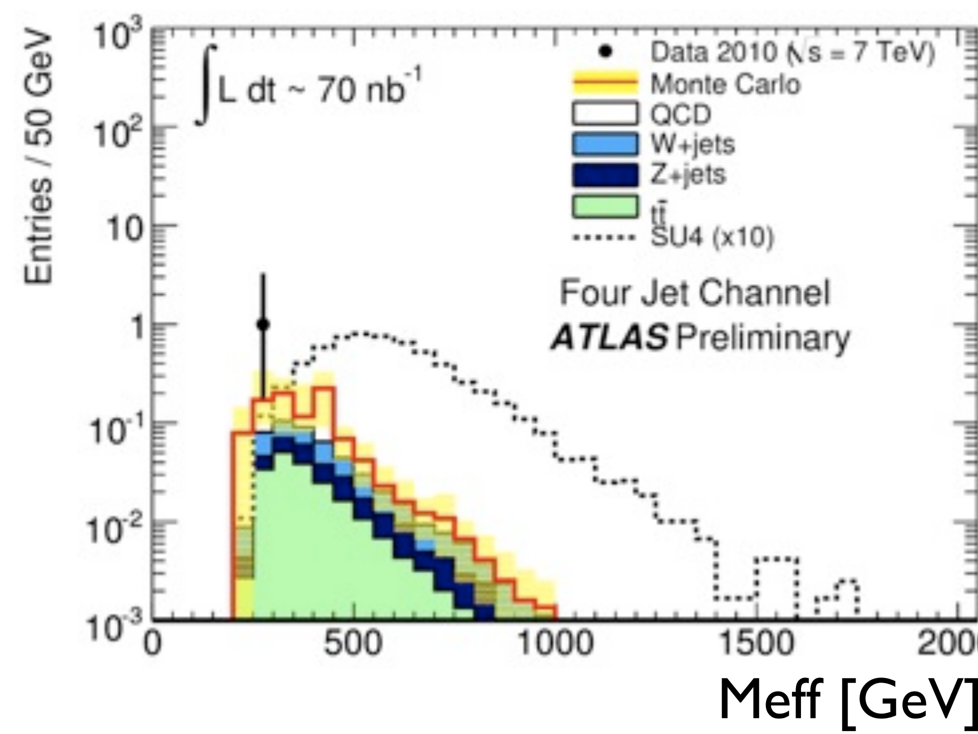
-- some information is carried away by two invisible particles

-- large combinatorial BG:  which jet (lepton) is which?

# huge background...




$$M_{\rm eff} = \sum_{i=1}^{4} |p_T^{(i)}| + E_T^{\rm miss}$$

# New Physics Signature

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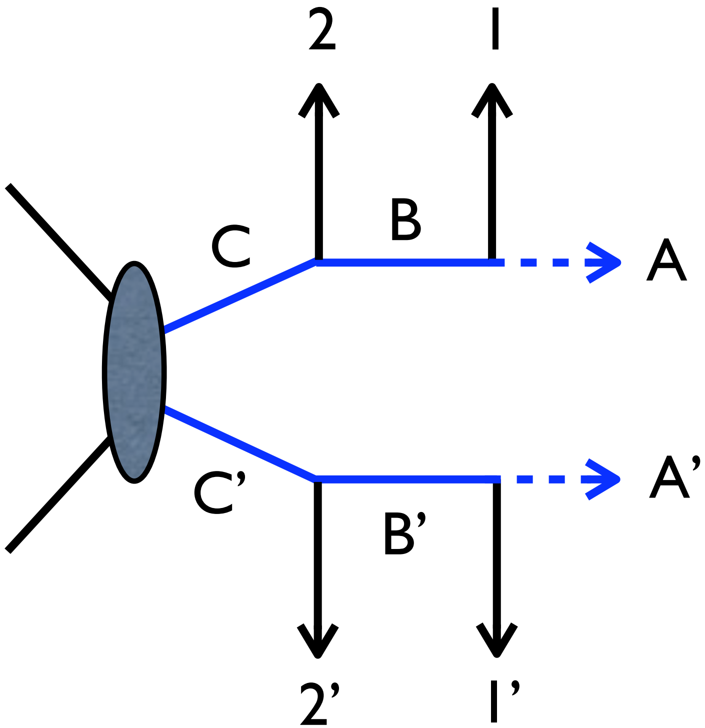
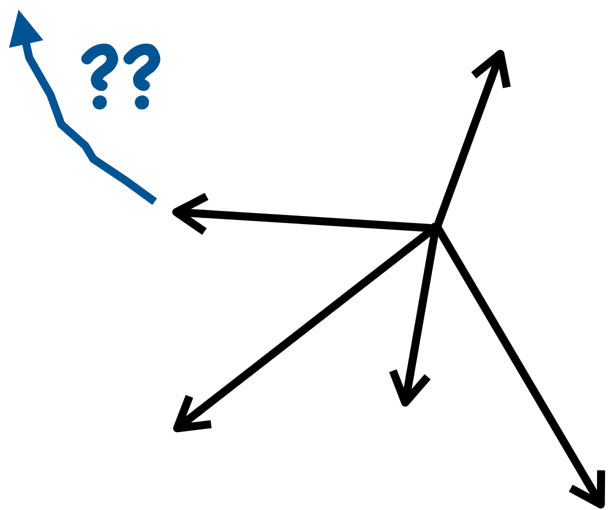



Non of new particle masses cannot be calculated without knowing $p_A$ or $p_{A'}$ .

$$(p_A)^2 = m_A^2$$
$$(p_1 + p_A)^2 = m_B^2$$
$$(p_2 + p_1 + p_A)^2 = m_C^2$$
$$\vdots$$




Which jet is which?

5! = 120 possible jet assignments

Observed 5 jets (1, 1', 2, 2' + ISR)

# New Physics Signature

New physics events contain **many jets (and lepton)** and **large missing energy** carried by two invisible particles.

## ❖ Advantage

-- can distinguish new physics signature from huge SMBG

## ❖ Disadvantages

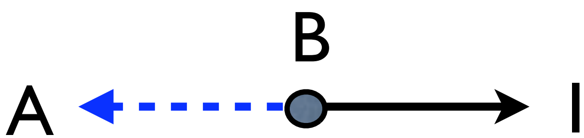
-- some information is carried away by two invisible particles

-- large combinatorial BG: which jet (lepton) is which?

**How we can measure new particle masses?**

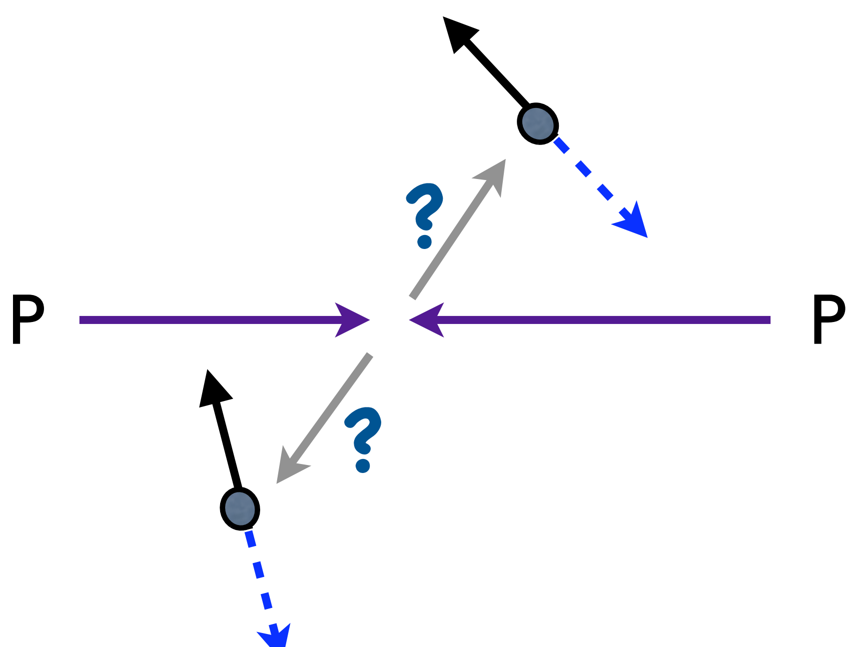
# Jet energy

- Energy of jet has information of masses at rest frame of BSM particle.



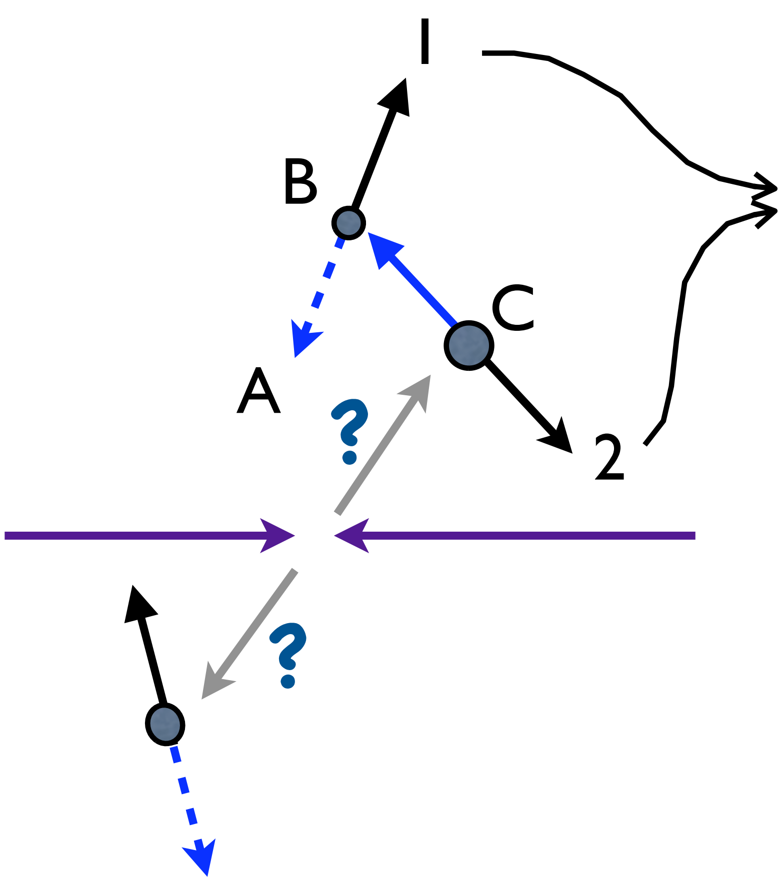

$$E_1 = \frac{m_B^2 - m_A^2}{2m_B}$$ at rest frame of B

- However it alters by unknown velocity of B . . .



# Invariant mass

I.Hinchliffe, F.E.Paige, M.D.Shapiro, J.Soderqvist, W.Yao, '96

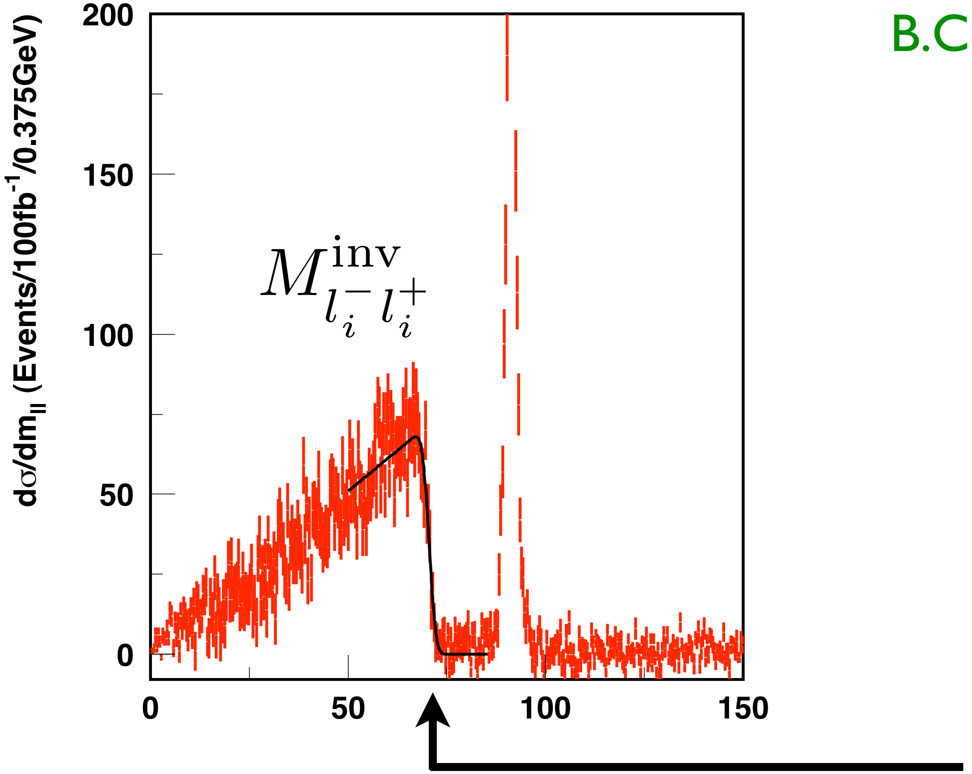



$$M_{\text{inv}}^2 = (p_1 + p_2)^2$$

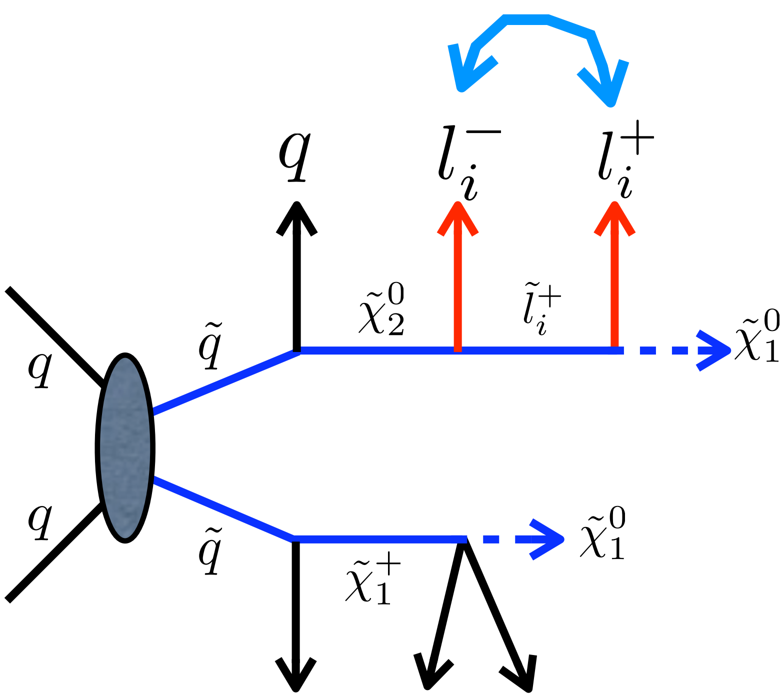
$$= \frac{(m_C^2 - m_B^2)(m_B^2 - m_A^2)}{m_B^2}\left(\frac{1-\cos\theta}{2}\right)$$

- independent of unknown velocity of C
- depends on angle, θ, between 1 and 2
- has maximum at cosθ = -1

B.C.Allanach, C.G.Lester, M.A.Parker, B.R.Webber '00




$$\frac{\sqrt{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}})(m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1})}}{m_{\tilde{l}}}$$



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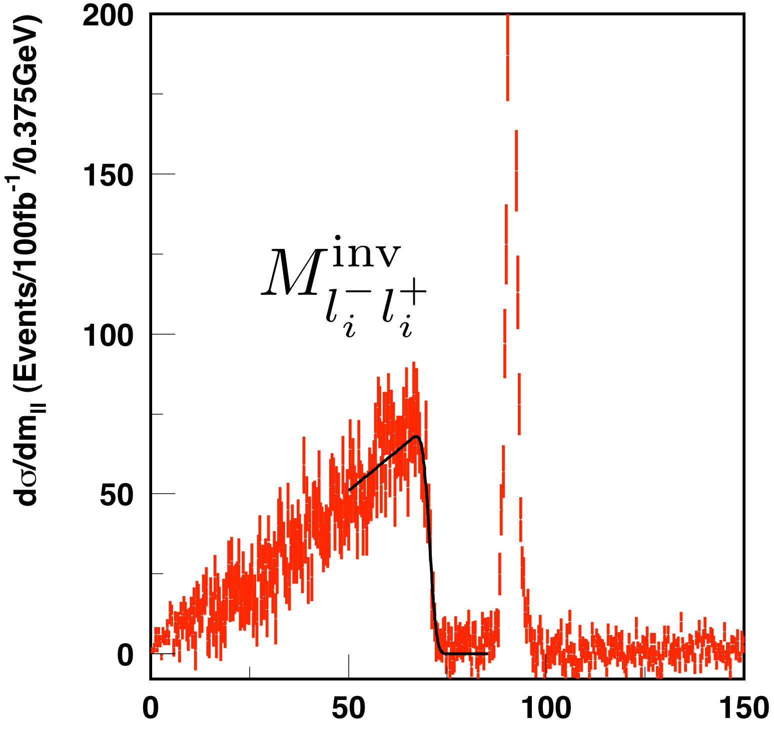


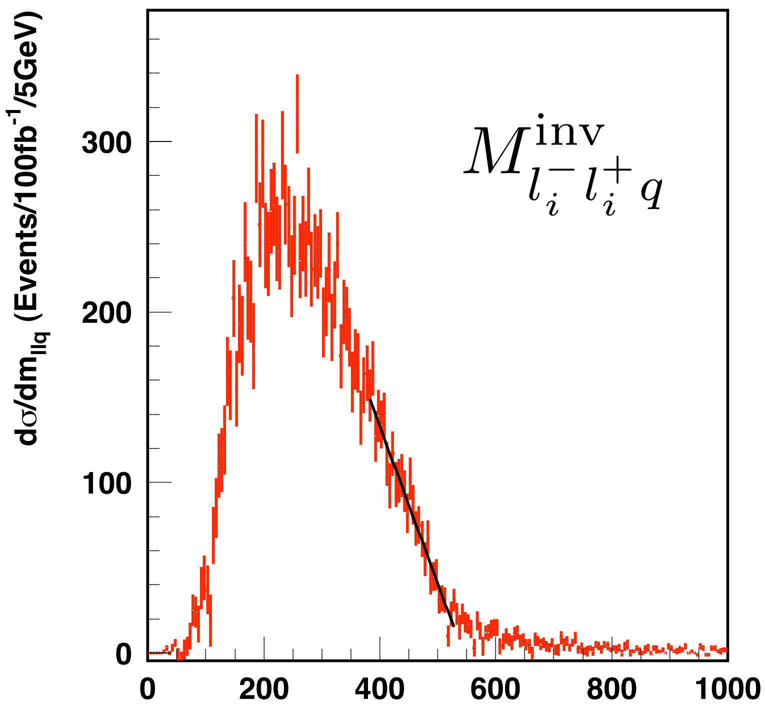


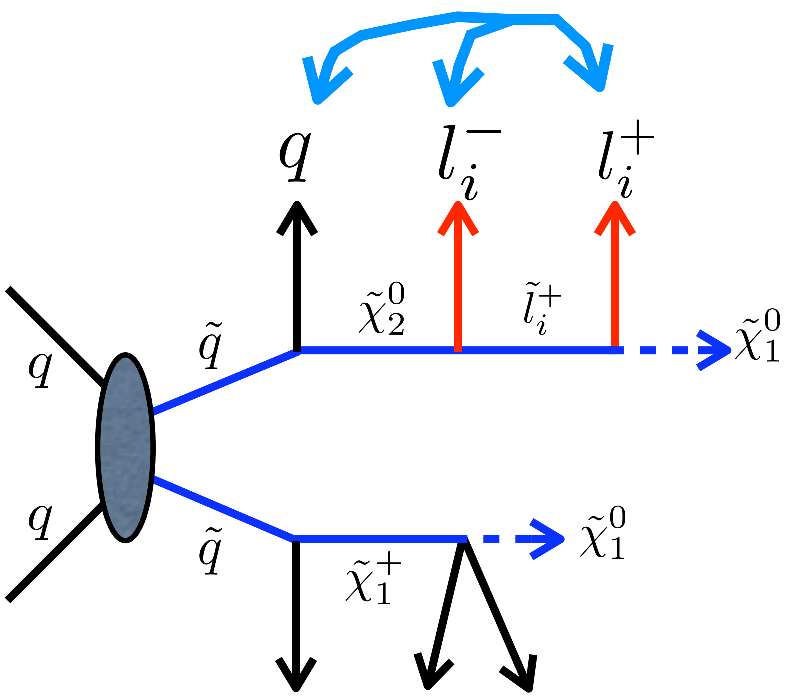

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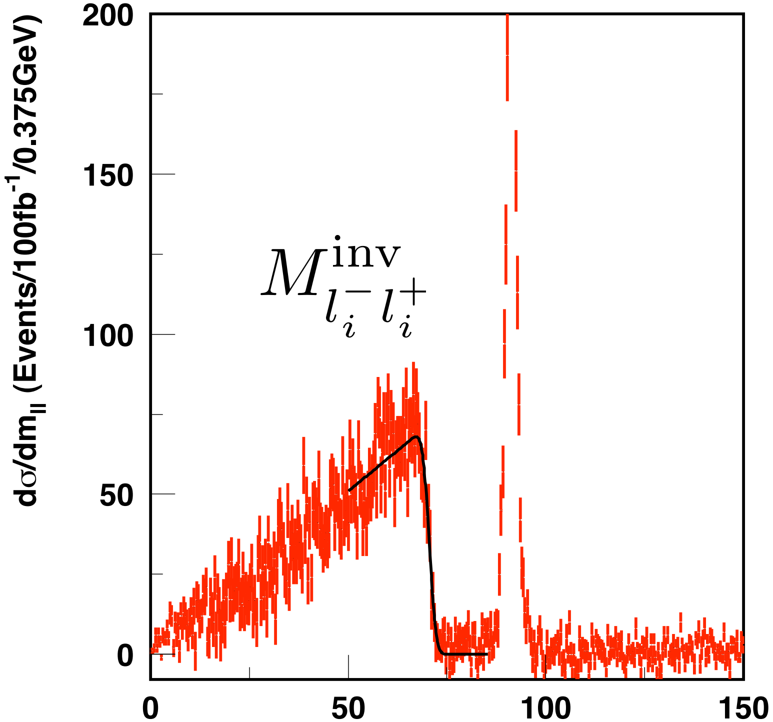
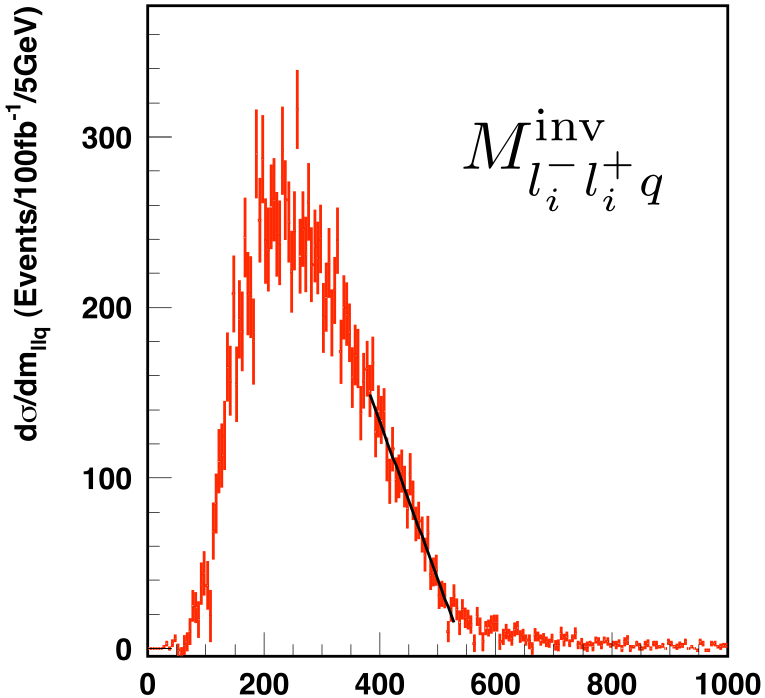
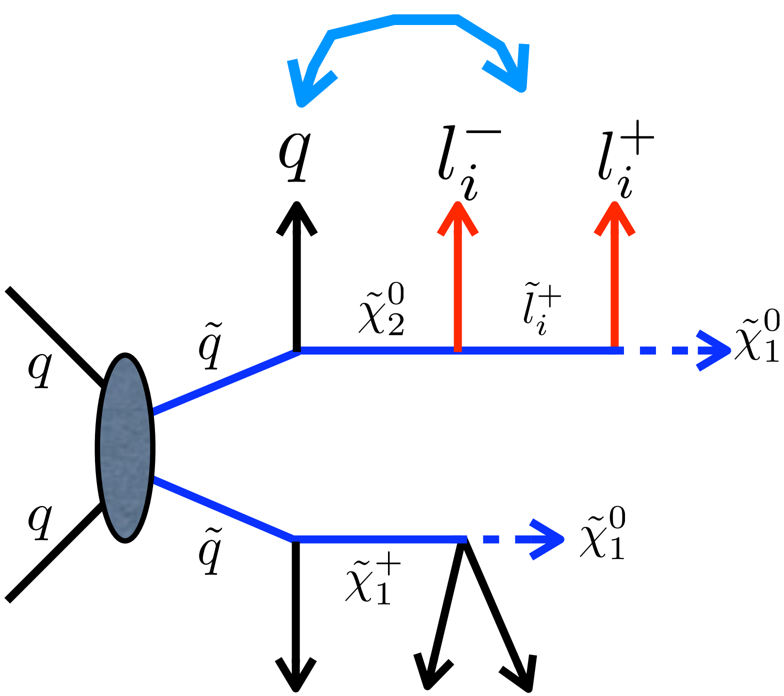
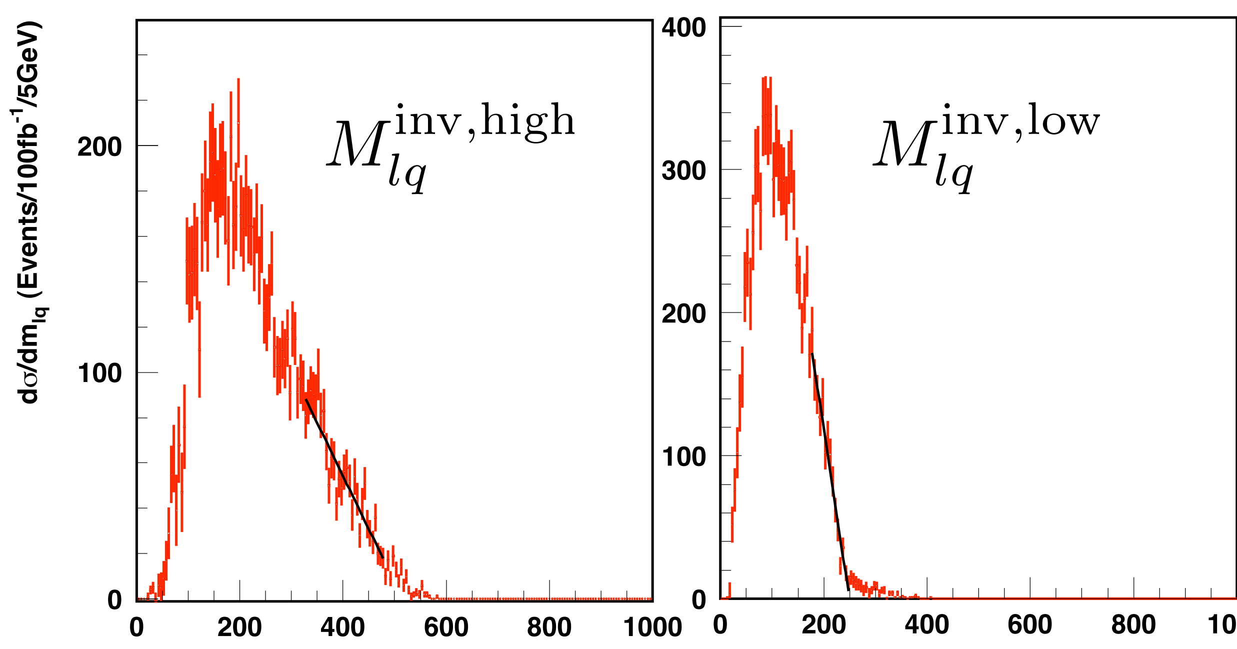


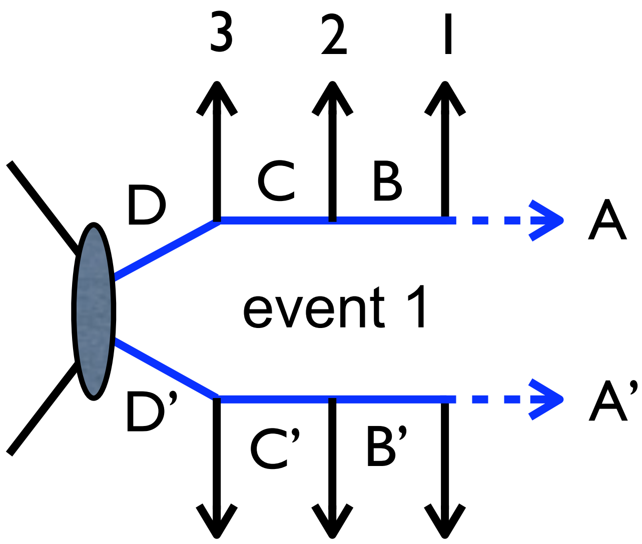



# Solving events

K. Kawagoe, M.M.Nojiri,
G.Polesello '05




$$m_A^2 = (p_A)^2$$
$$m_B^2 = (p_1 + p_A)^2$$
$$m_C^2 = (p_2 + p_1 + p_A)^2$$
$$\vdots$$

} mass shell constraints

$$p_{T\text{miss}}^{x(y)} = p_A^{x(y)} + p_{A'}^{x(y)}$$

} $p_{T\text{miss}}$ constraints

# of mass shell constraints = 8

pTmiss measurement = 2

**# of total constraints = 10**

# of missing momentum components = 8

# of unknown masses = 4

**# of total unknown parameters = 12**

# Solving events

K. Kawagoe, M.M.Nojiri,
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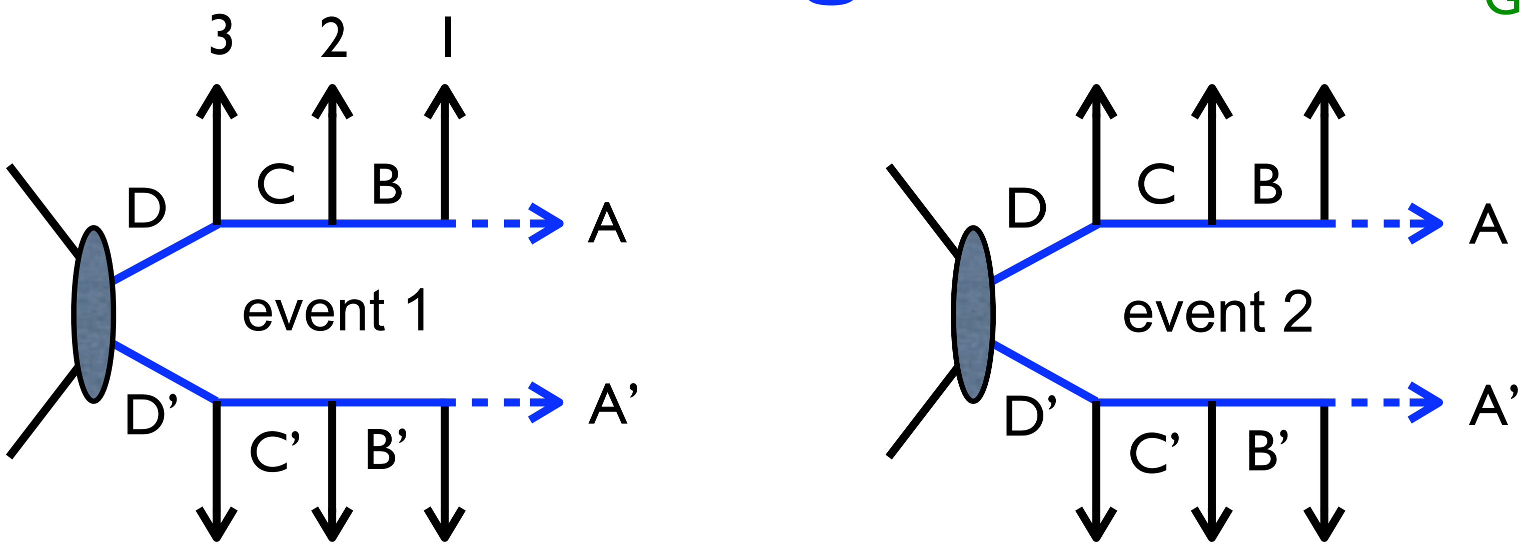



| | | | |
|---|---|---|---|
| # of mass shell constraints | = 8 | $\longrightarrow$ | 16 |
| pTmiss measurement | = 2 | $\longrightarrow$ | 4 |
| **# of total constraints** | **= 10** | $\longrightarrow$ | **20** |
| # of missing momentum components | = 8 | $\longrightarrow$ | 16 |
| # of unknown masses | = 4 | $\longrightarrow$ | 4 |
| **# of total unknown parameters** | **= 12** | $\longrightarrow$ | **20** |

All unknown parameters can be determined by using "only" 2 events.

# Solving events

In general,

**# of total constraints**

= [(# of BSM particles appear in chains) + 2 ] × $N_{events}$

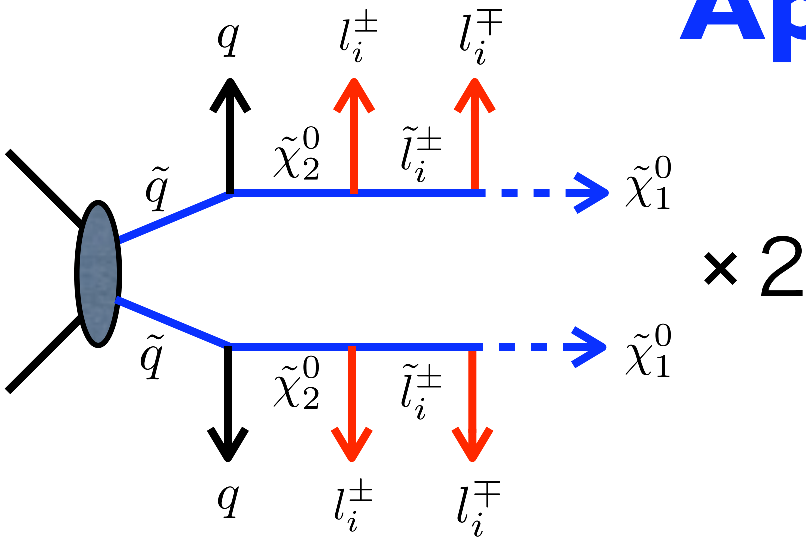
**# of total unknown parameters**

= 8 $N_{events}$ + (# of unknown masses)

***need long decay chains to solve events***

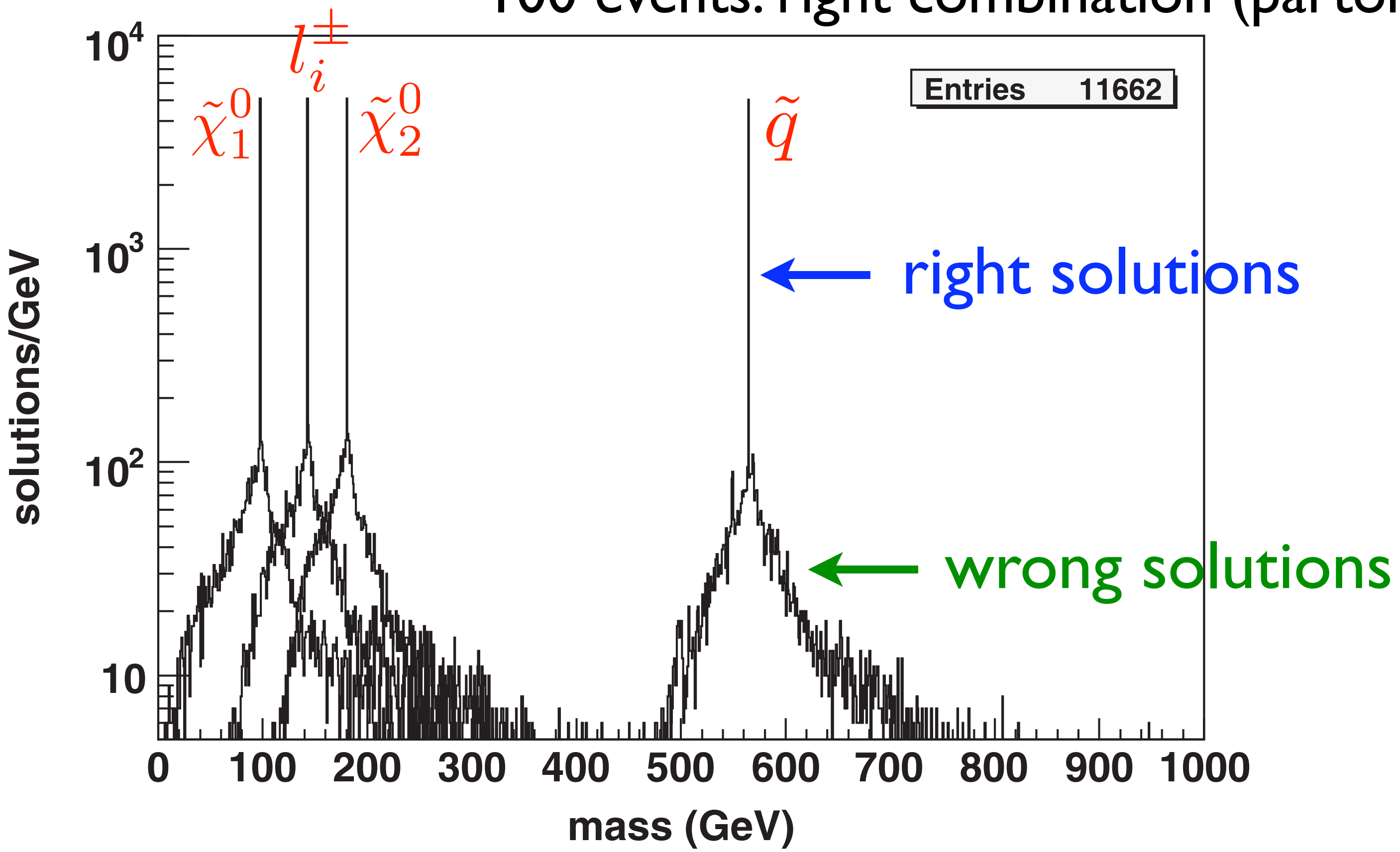
# Application

H-C.Cheng, J.F.Gunion, Z.Han, B.McElrath '09




There are up to 8 physical solutions, because constraints end up with an eighth polynomial equation.

100 events: right combination (parton level)



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H-C.Cheng, J.F.Gunion,
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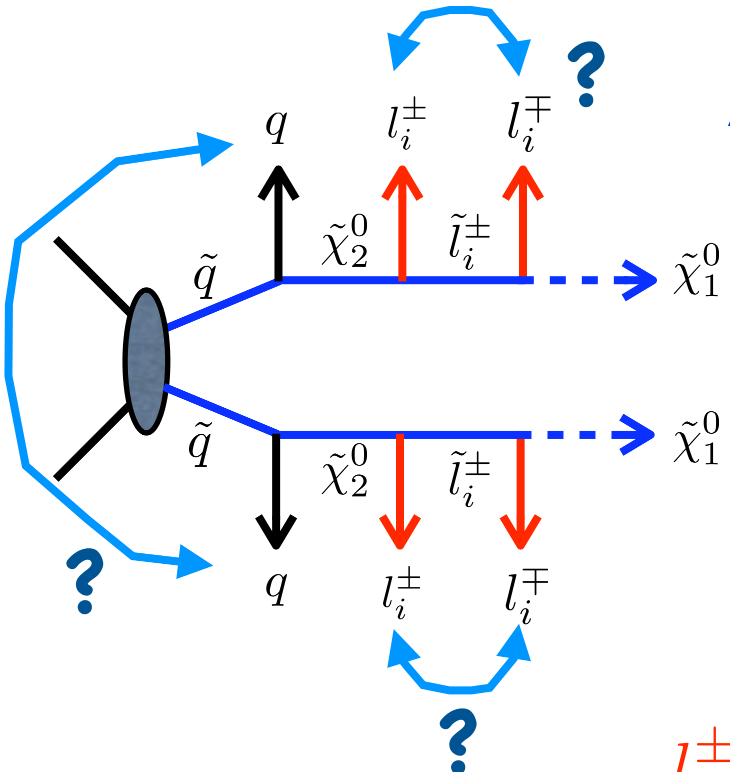
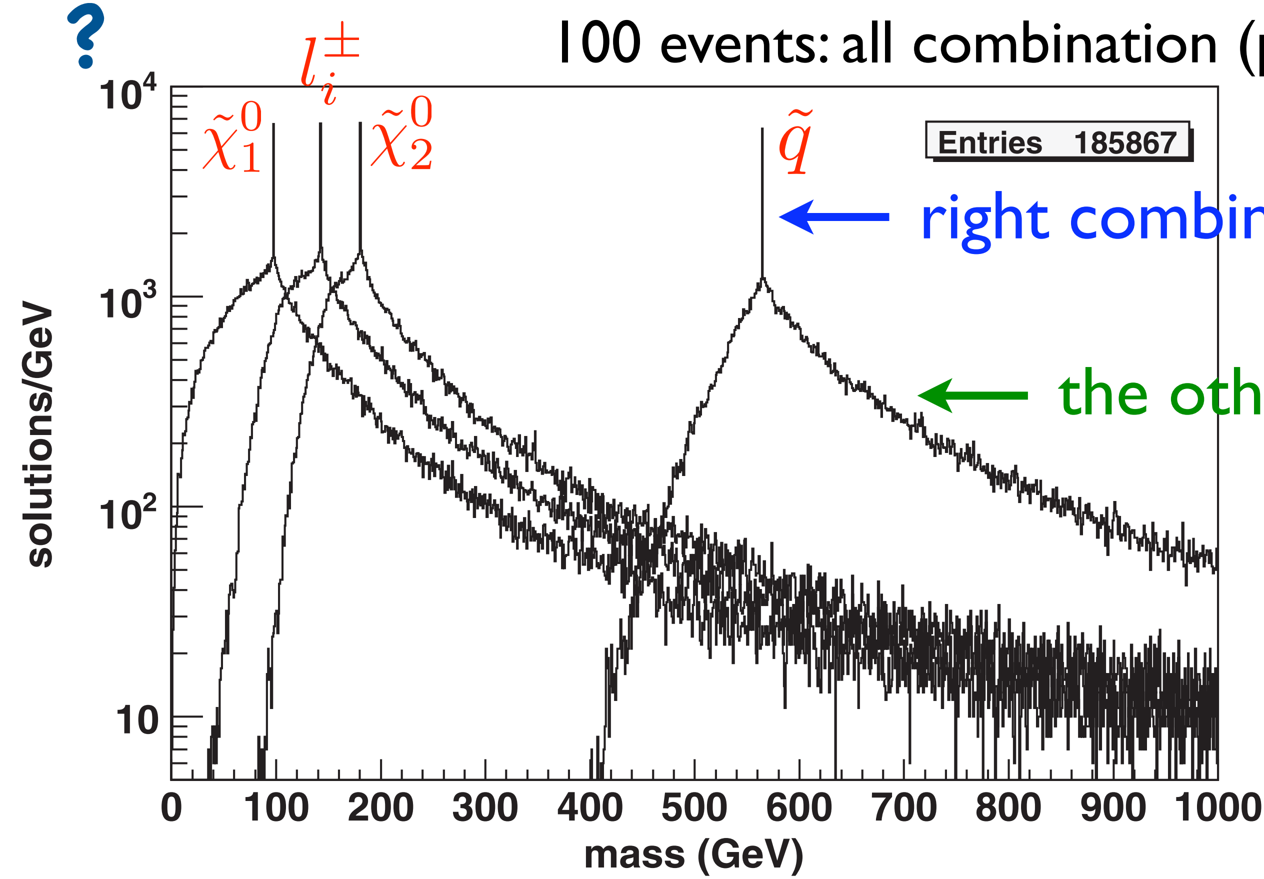



$\times 2$

Because detector can not distinguish which lepton (jet) is which, there are up to $16^2$ combinatorial background.

100 events: all combination (parton level)



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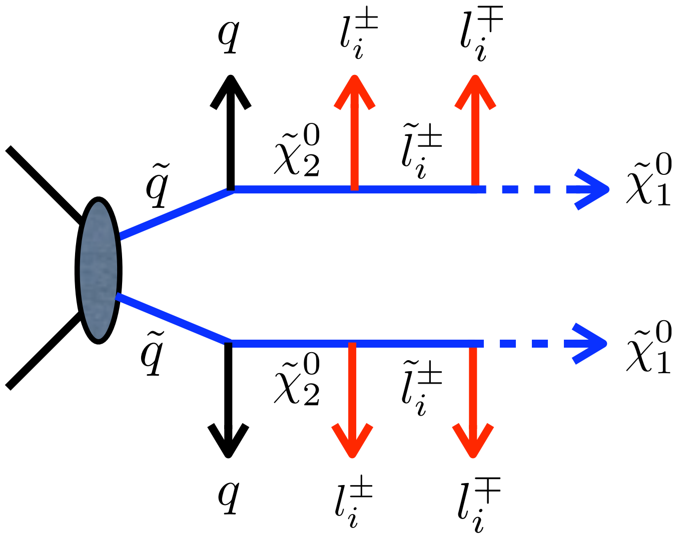
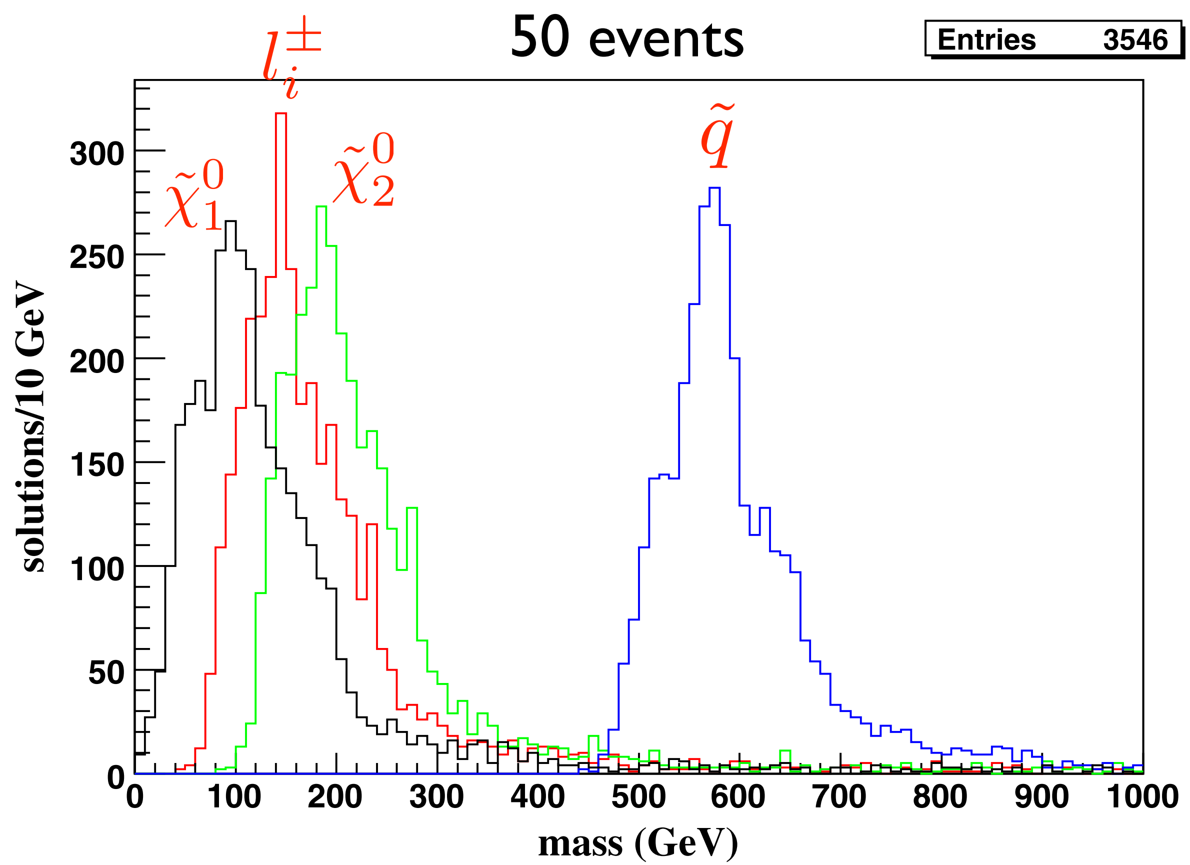
H-C.Cheng, J.F.Gunion, Z.Han, B.McElrath '09



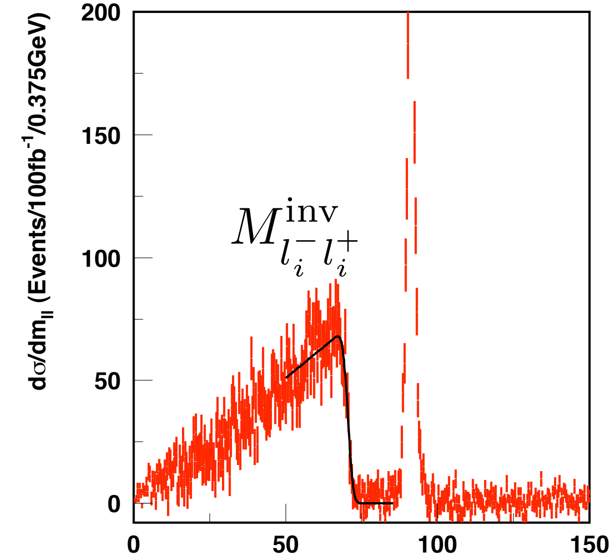

$\times 2$

Background and detector effects are included.



# Including inv. mass analysis

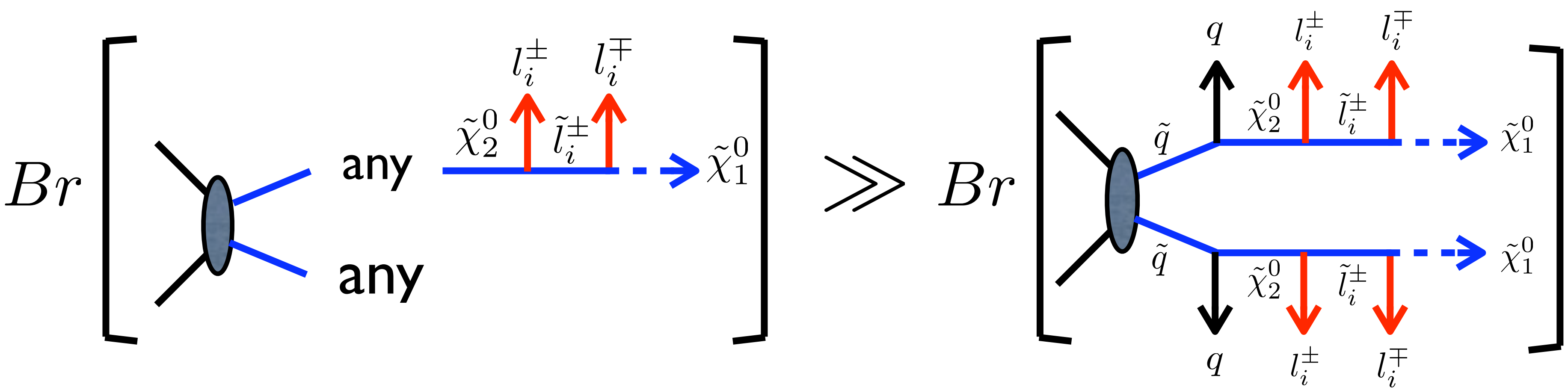
- End point of the dilepton mass distribution is often the most precise measurement in new physics mass measurements.




error $\lesssim$ 0.5% (10 fb$^{-1}$)

i) free from jet energy resolution

ii) has statistical advantage

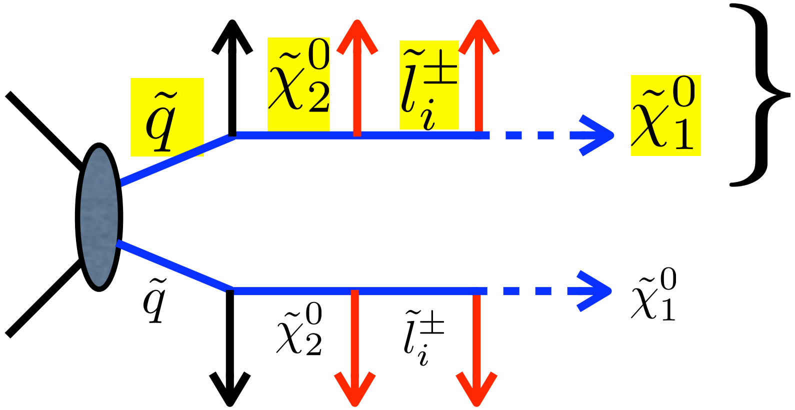



**One may improve the analysis by including dilepton mass measurement**

# Including inv. mass analysis

M.M.Nojiri, K.S, B.R.Webber '10

- exchange variables

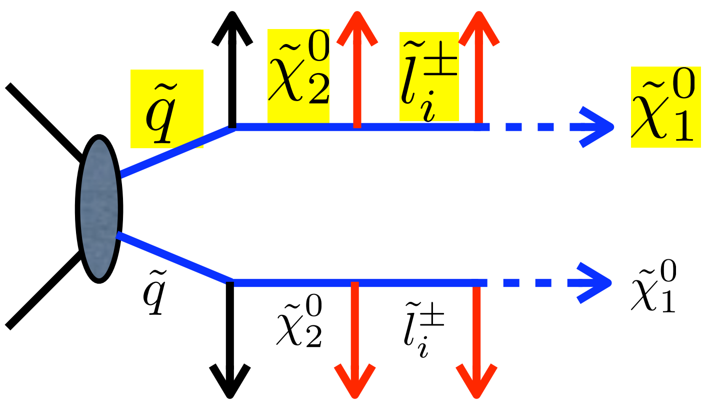


$$\left.\begin{array}{l} M_1 = m_{\tilde{l}}^2 - m_{\tilde{\chi}_1^0}^2 \\ M_2 = m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}}^2 \\ M_3 = m_{\tilde{q}}^2 - m_{\tilde{\chi}_2^0}^2 \\ M_4 = M_{ll}^{\max} = (m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{l}}^2 \end{array}\right.$$

# Including inv. mass analysis

M.M.Nojiri, K.S, B.R.Webber '10

- exchange variables




$$M_1 = m_{\tilde{l}}^2 - m_{\tilde{\chi}_1^0}^2$$

$$M_2 = m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}}^2$$

$$M_3 = m_{\tilde{q}}^2 - m_{\tilde{\chi}_2^0}^2$$

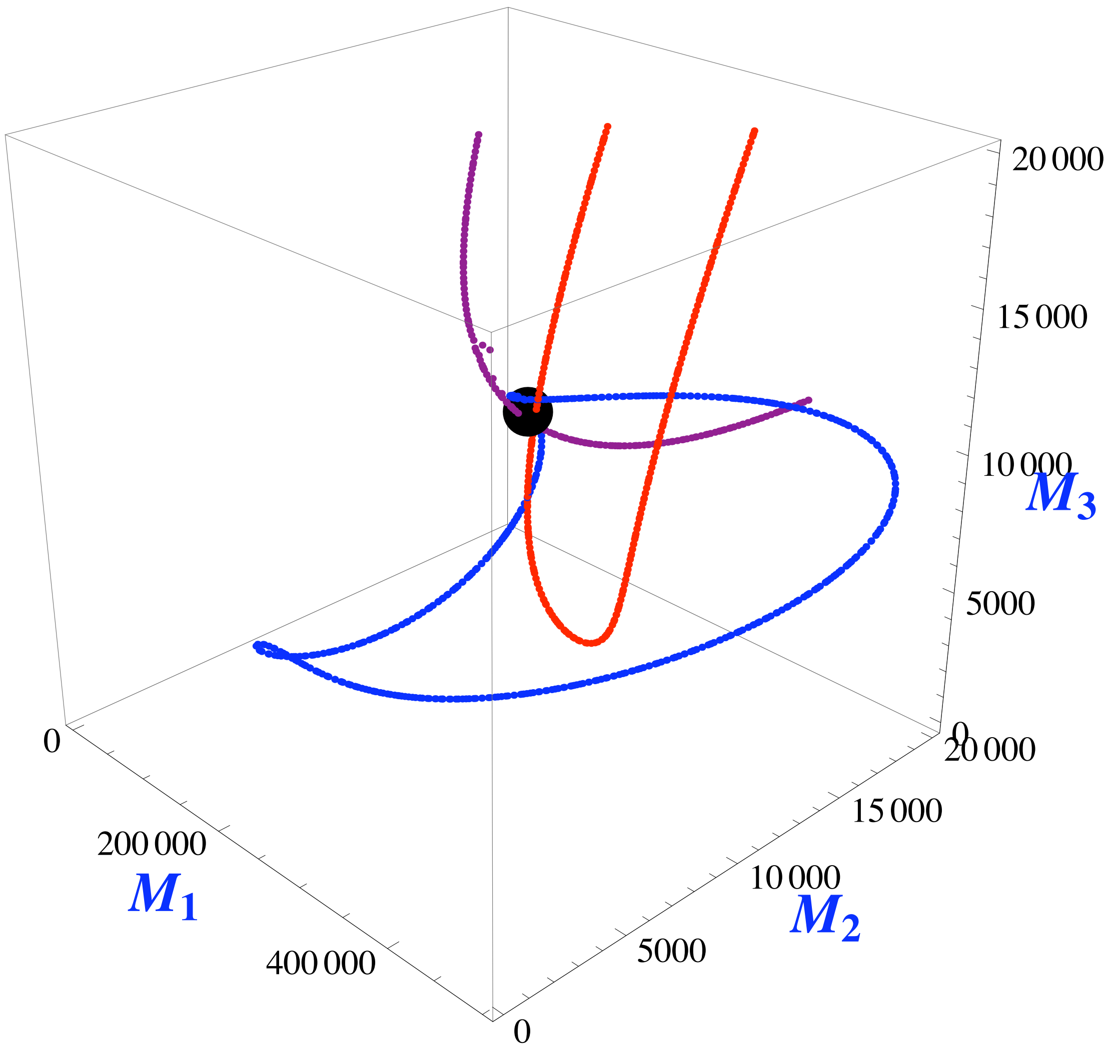
$$M_4 = M_{ll}^{\max} = (m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}}^2)(m_{\tilde{l}}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{l}}^2$$

fix $M_4$ by dilepton mass measurement

Since the number of unknown masses is reduced to three ($M_1$, $M_2$, $M_3$), we can visualise event by event constraint.

# Including inv. mass analysis

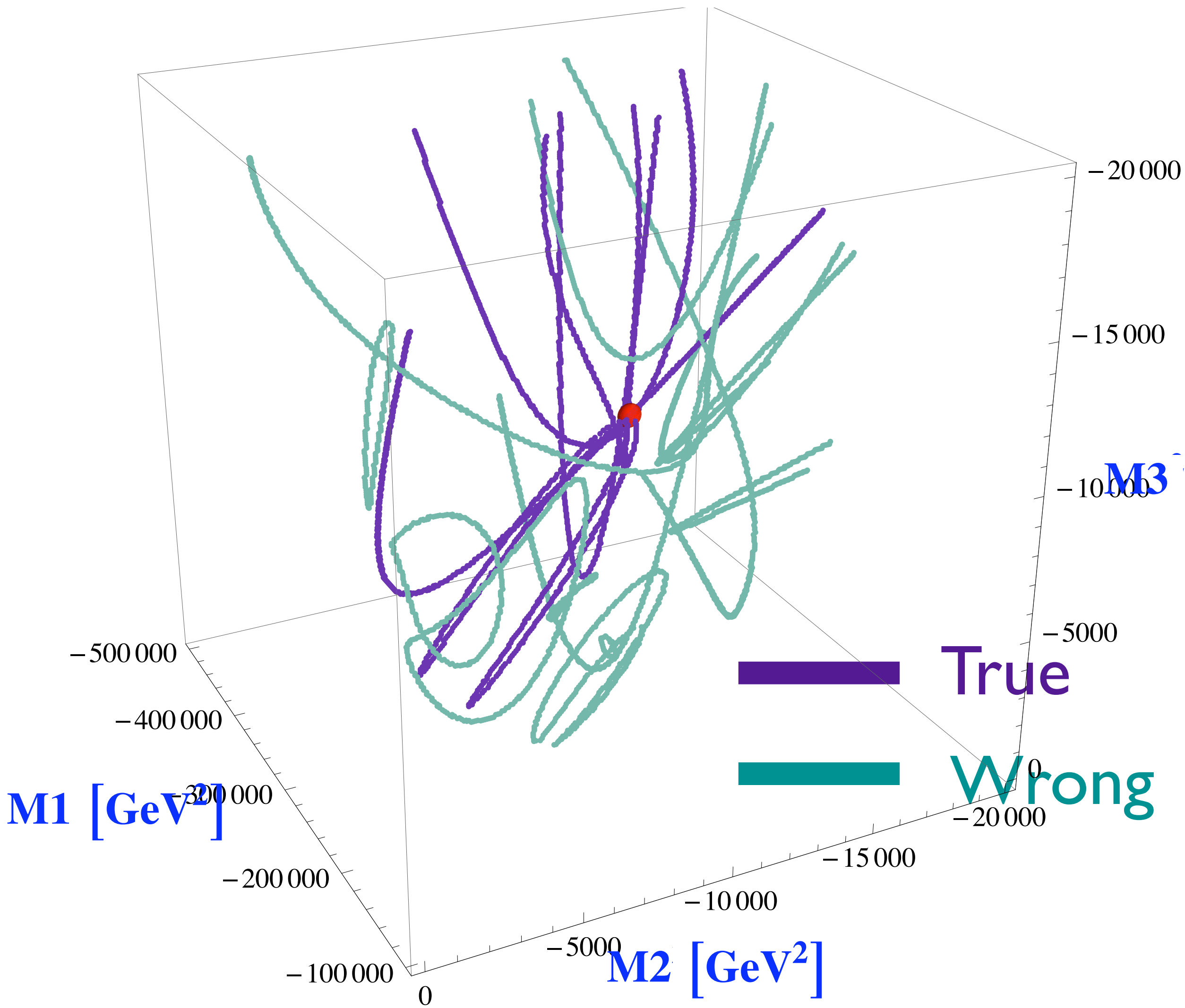
3 events: right combination
(parton level)




- Each event (&assignment) constrains three masses on a curve.
- More than one event can pin down the right masses at an intersection of the curves.

# Including inv. mass analysis

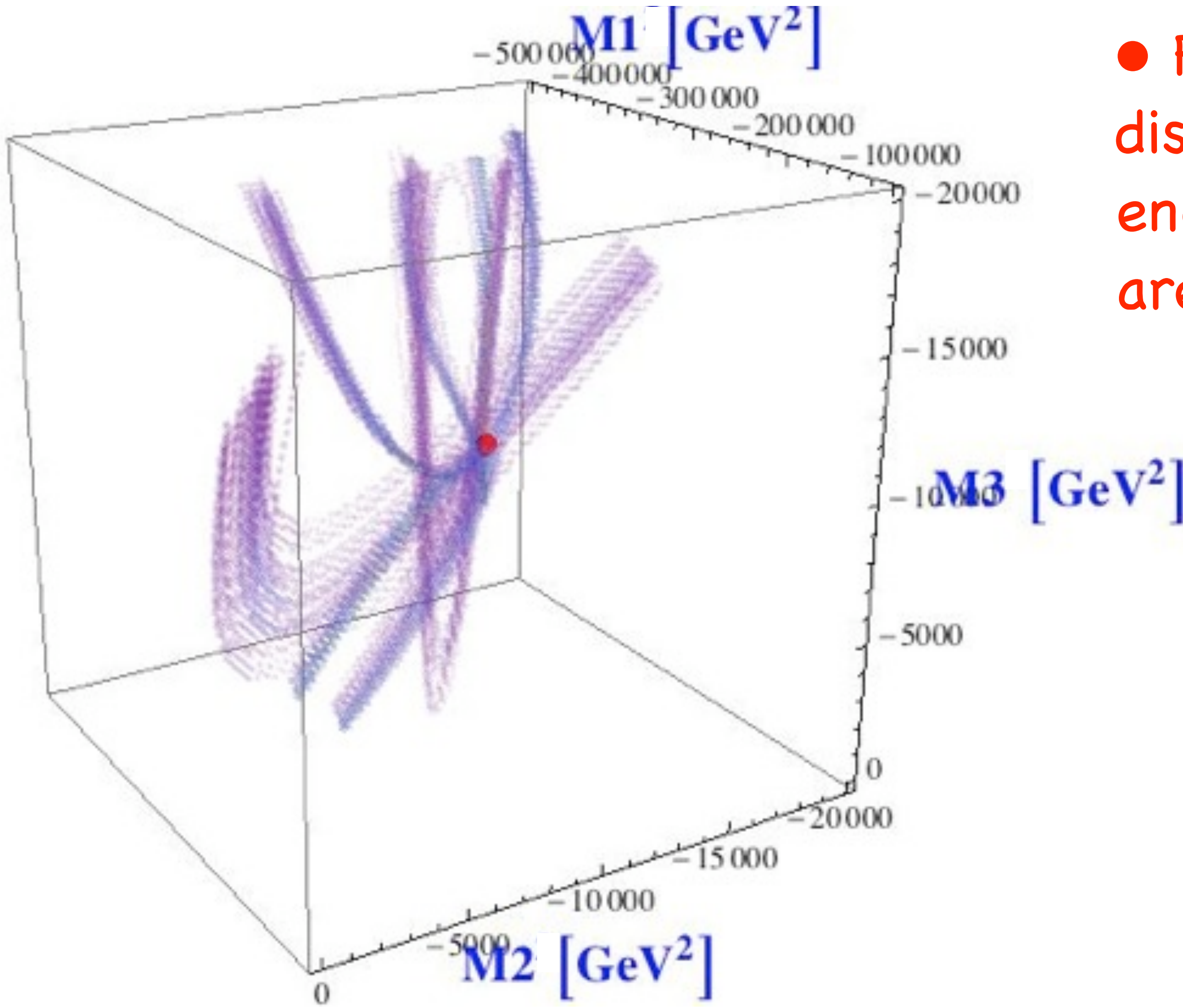
5 events:
all combination
(parton level)




- Curves from wrong combination do not have intersection.

# Including inv. mass analysis

5 events: right combination




- Finite detector resolution distorts curves. As jet energy is smeared, curves are also smeared.

# Error estimation

## 1. generate fake events

For each observed event, we generate 1000 "fake" events whose momenta of jets and missing are deviate from observed ones, according to Gaussian type error functions.

for jets: $\frac{\sigma_E}{E} = \frac{0.5}{\sqrt{E}} + 0.03, \qquad \sigma_\phi = \frac{0.4}{\sqrt{E}} + 0.015, \qquad \sigma_\eta = \frac{0.3}{\sqrt{E}} + 0.02,$

for missing momentum: $\frac{\sigma_E}{E} = \frac{0.5}{\sqrt{E}} + 0.03, \qquad \sigma_\phi = \frac{0.8}{\sqrt{E}} + 0.06,$

## 2. define probability density

Probability density, f(**M**), can be obtained up to normalisation by counting how many curves are passing through a cell, **M**.

## 3. get likelihood function

$\Delta\chi^2$ or log(L) can be obtained by

$$\ln L(\mathbf{M}) = \sum_{i_{\rm ev}}^{N} \ln f_{i_{\rm ev}}(\mathbf{M}) \qquad \Delta\chi^2(\mathbf{M}) = 2(\ln L(\mathbf{M})_{\rm max} - \ln L(\mathbf{M})),$$

# MC simulation

- 3 model points are examined

| | $m_0$ | $m_{1/2}$ | $A_0$ | $\tilde{\chi}_1^0$ | $\tilde{e}_R$ | $\tilde{\chi}_2^0$ | $\tilde{u}_L$ |
|---|---|---|---|---|---|---|---|
| Point A | 110 | 220 | 0 | 86 | 142 | 161 | 504 |
| Point B | 100 | 250 | $-100$ | 99 | 141 | 186 | 563 |
| Point C | 140 | 260 | 0 | 103 | 174 | 193 | 592 |

$m_0^{\text{3rd gene.}} = 300\,\text{GeV}$

to forbid $\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau \to \tilde{\chi}_1^0 \tau^+ \tau^-$

- 500,000 inclusive SUSY events are generated by Herwig, corresponding to 10, 15 and 20 fb$^{-1}$ for Points A, B and C, respectively.

- Effects of SUSY BG, hadronisation, parton shower, underlying events and detector resolution (AcerDET) are included

- The parameter space is divided into cells:

$$\Delta M_1 = 5000, \ \Delta M_2 = 400, \ \Delta M_3 = 600 \ \text{ in } \ \text{GeV}^2$$

# Cut

- The following cuts have been applied to reduce BG

  **(i)** $M_{\rm eff} \equiv \sum_{i=1}^{4} p_T^{{\rm jet},i} + \sum_{i=1}^{4} p_T^{{\rm lep},i} + E_T^{\rm miss} > 400\,{\rm GeV}$ ;

  **(ii)** $E_T^{\rm miss} > \max(200\,{\rm GeV},\ 0.2 M_{\rm eff})$ ;

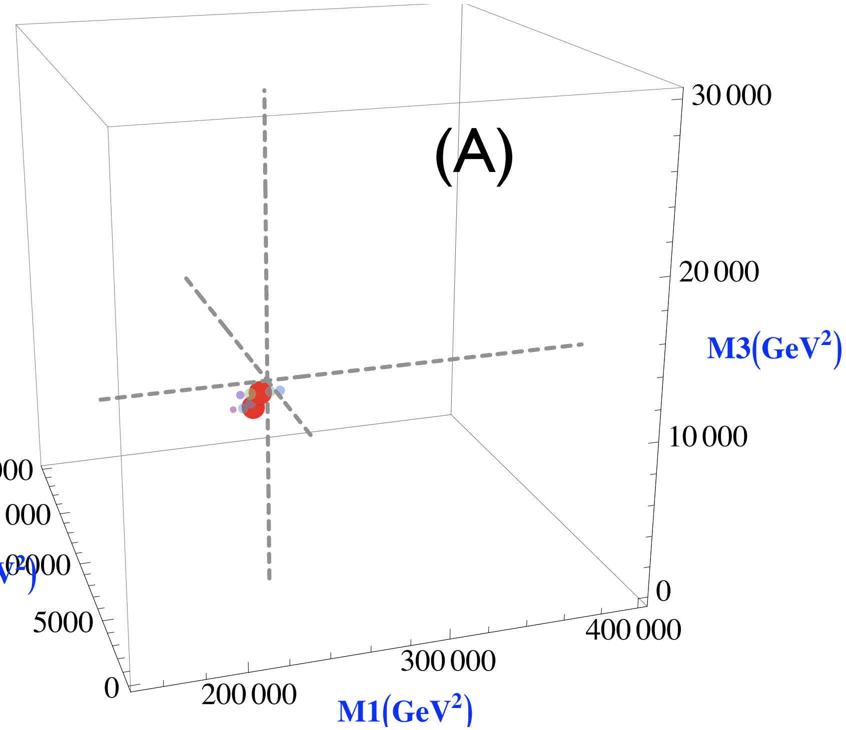
  **(iii)** At least two jets with $p_T^{{\rm jet},1} > 100\,{\rm GeV}$ and $p_T^{{\rm jet},2} > 50\,{\rm GeV}$ within $|\eta| < 2.5$ ;

  **(iv)** Two pairs of opposite sign same flavour leptons with $p_T > 20\,{\rm GeV}$ and $|\eta| < 3$ ;

  **(v)** No $b$ jet with $p_T > 30\,{\rm GeV}$ and $|\eta| < 3$ .

- The main SM-BG is $t\bar{t} \to b\bar{b}W^+W^- \to 2l^+2l^-2j + E_T^{\rm miss}$.

  It is negligible after the cut. (about 10% of SUSY-BG)



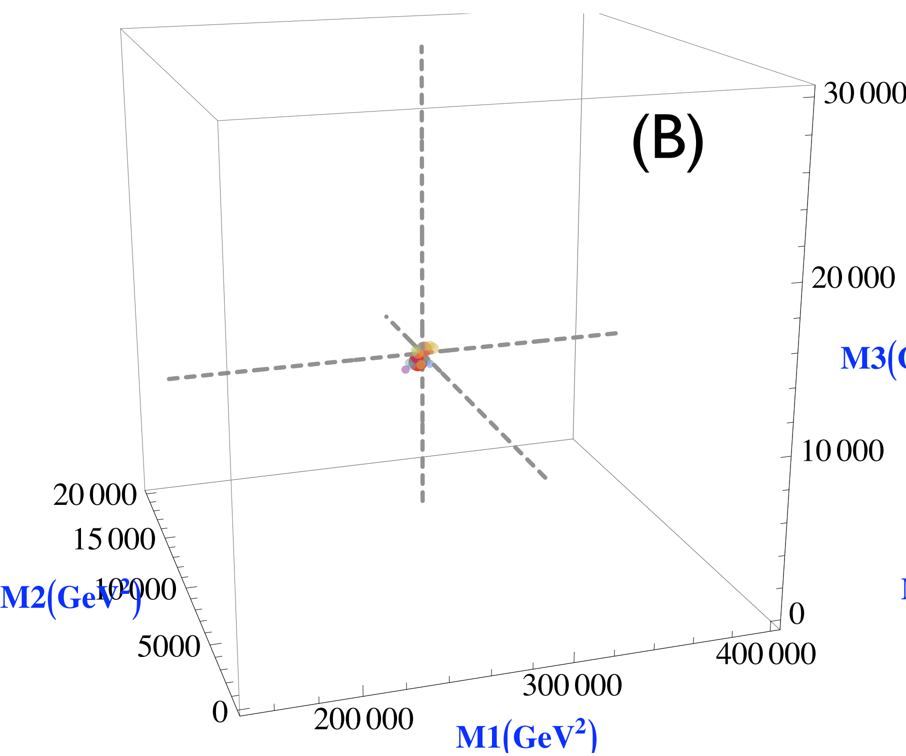

# Result:

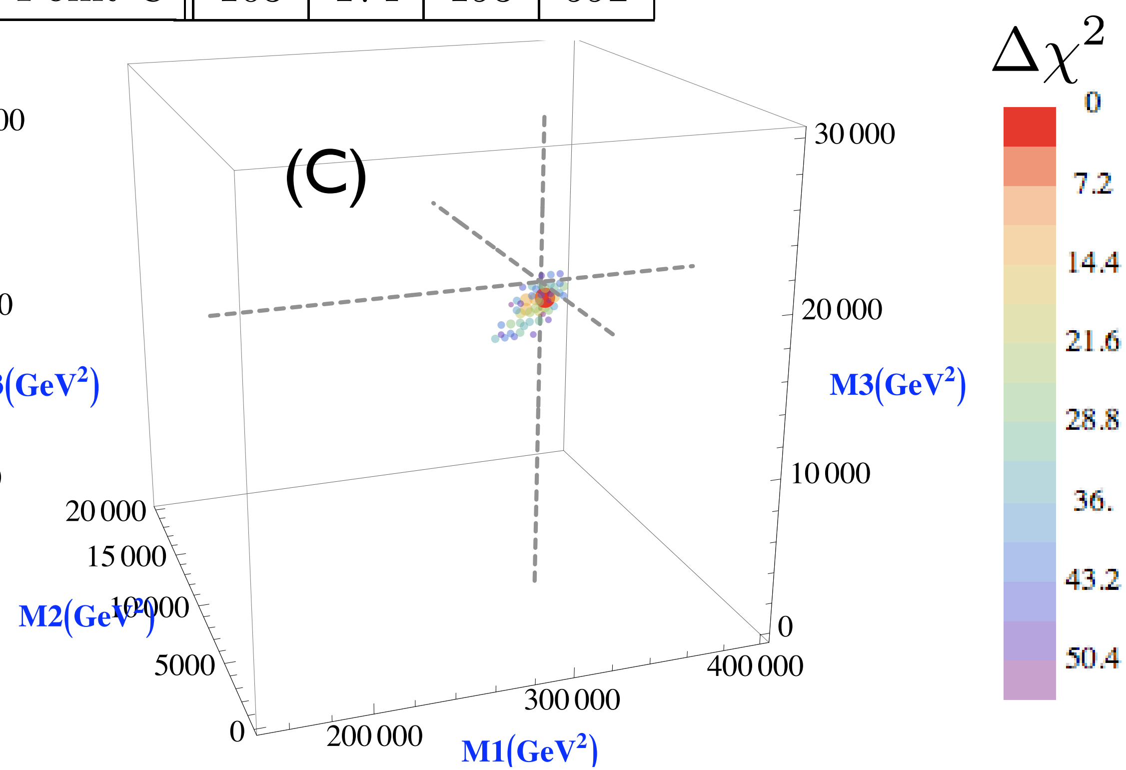
M.M.Nojiri, K.S, B.R.Webber '10

| | $\tilde{\chi}^0_1$ | $\tilde{e}_R$ | $\tilde{\chi}^0_2$ | $\tilde{u}_L$ |
|---|---|---|---|---|
| Point A | $68.2^{+16.2}_{-5.8}$ | $127.9^{+12.6}_{-4.2}$ | $146.1^{+13.0}_{-4.4}$ | $493.8^{+11.5}_{-3.8}$ |
| Point B | $94.5^{+8.5}_{-2.8}$ | $137.2^{+9.1}_{-3.1}$ | $181.7^{+8.5}_{-2.8}$ | $561.7^{+9.4}_{-3.1}$ |
| Point C | $95.6^{+5.1}_{-5.3}$ | $167.4^{+3.9}_{-3.9}$ | $186.1^{+4.0}_{-4.0}$ | $593.4^{+3.4}_{-3.4}$ |

| | $\tilde{\chi}^0_1$ | $\tilde{e}_R$ | $\tilde{\chi}^0_2$ | $\tilde{u}_L$ |
|---|---|---|---|---|
| Point A | 86 | 142 | 161 | 504 |
| Point B | 99 | 141 | 186 | 563 |
| Point C | 103 | 174 | 193 | 592 |

# Input:

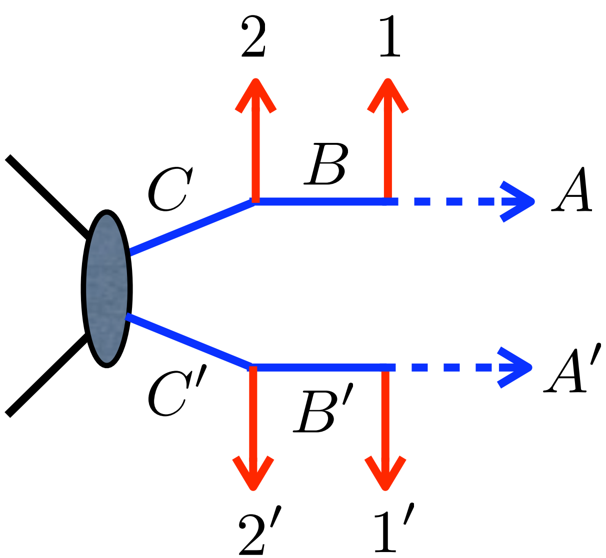


# Under constrained decay chains

H-C.Cheng, J.F.Gunion, Z.Han, G.Marandella, B.McElrath '07

- For short decay chains, unknown parameters (masses and pA, pA') are not solvable, because of lack of mass shell constraints.




-- Constraints --

$$m_A^2 = (p_A)^2$$
$$m_B^2 = (p_1 + p_A)^2$$
$$m_C^2 = (p_2 + p_1 + p_A)^2$$

+ [ for pA' ]

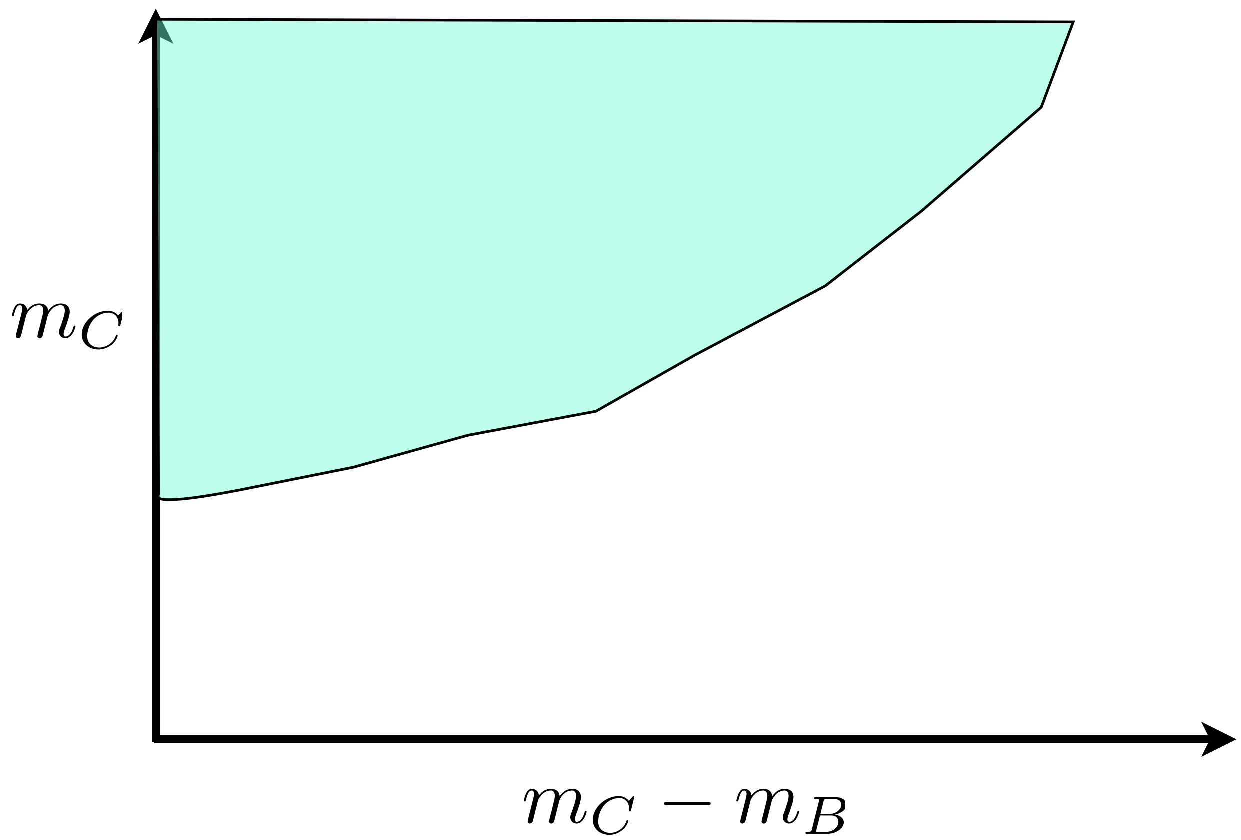
$$p_{T\text{miss}}^{x(y)} = p_A^{x(y)} + p_{A'}^{x(y)}$$

- If one scans whole possible values of pA and pA' compatible with pTmiss constraints, one can get allowed and excluded regions for each masses.

# Under constrained decay chains

H-C.Cheng, J.F.Gunion, Z.Han, G.Marandella, B.McElrath '07

- The regions are obtained event by event.

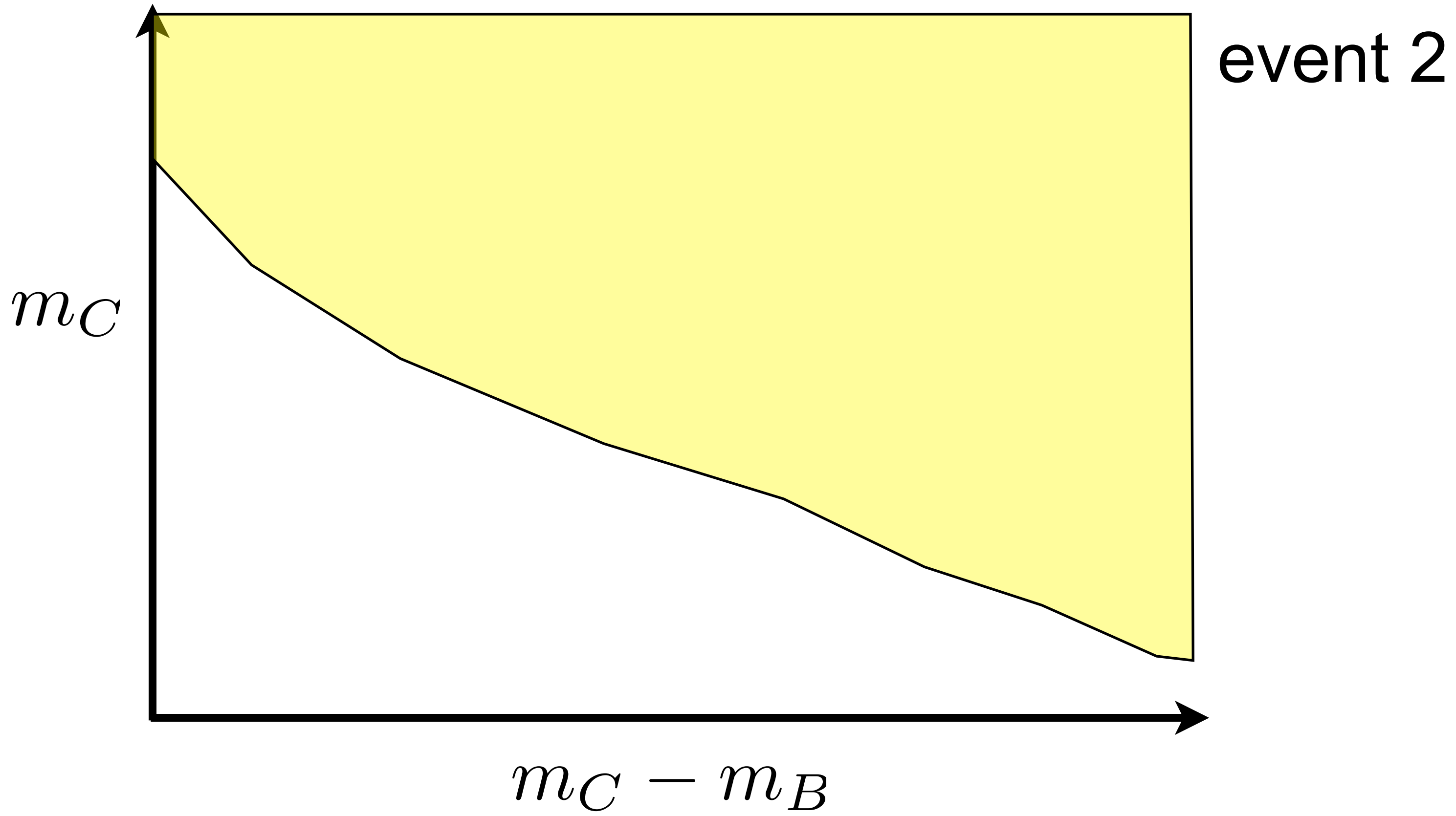



event 1

# Under constrained decay chains

H-C.Cheng, J.F.Gunion, Z.Han, G.Marandella, B.McElrath '07

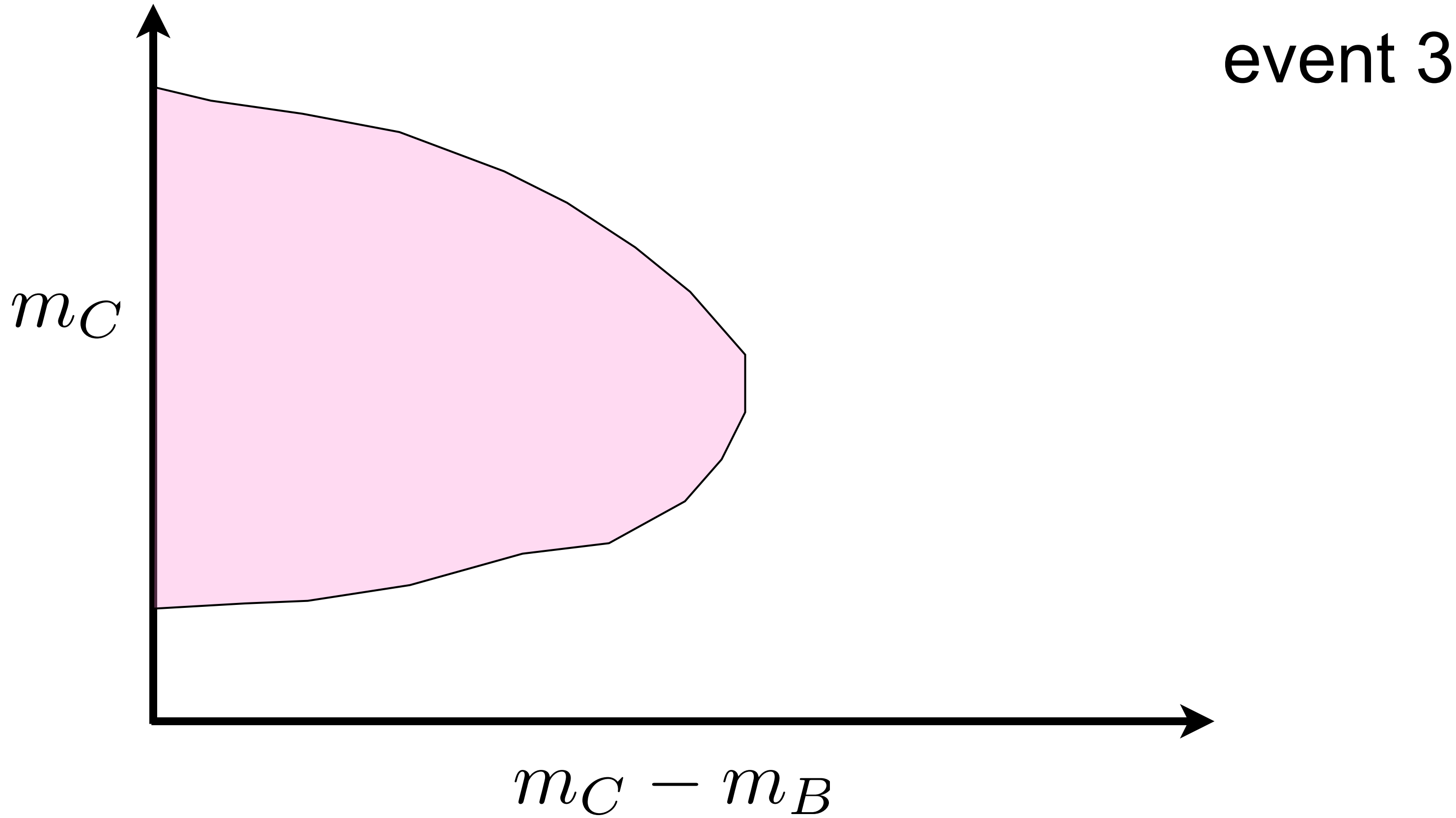
- Event by event allowed region



# Under constrained decay chains

H-C.Cheng, J.F.Gunion, Z.Han, G.Marandella, B.McElrath '07

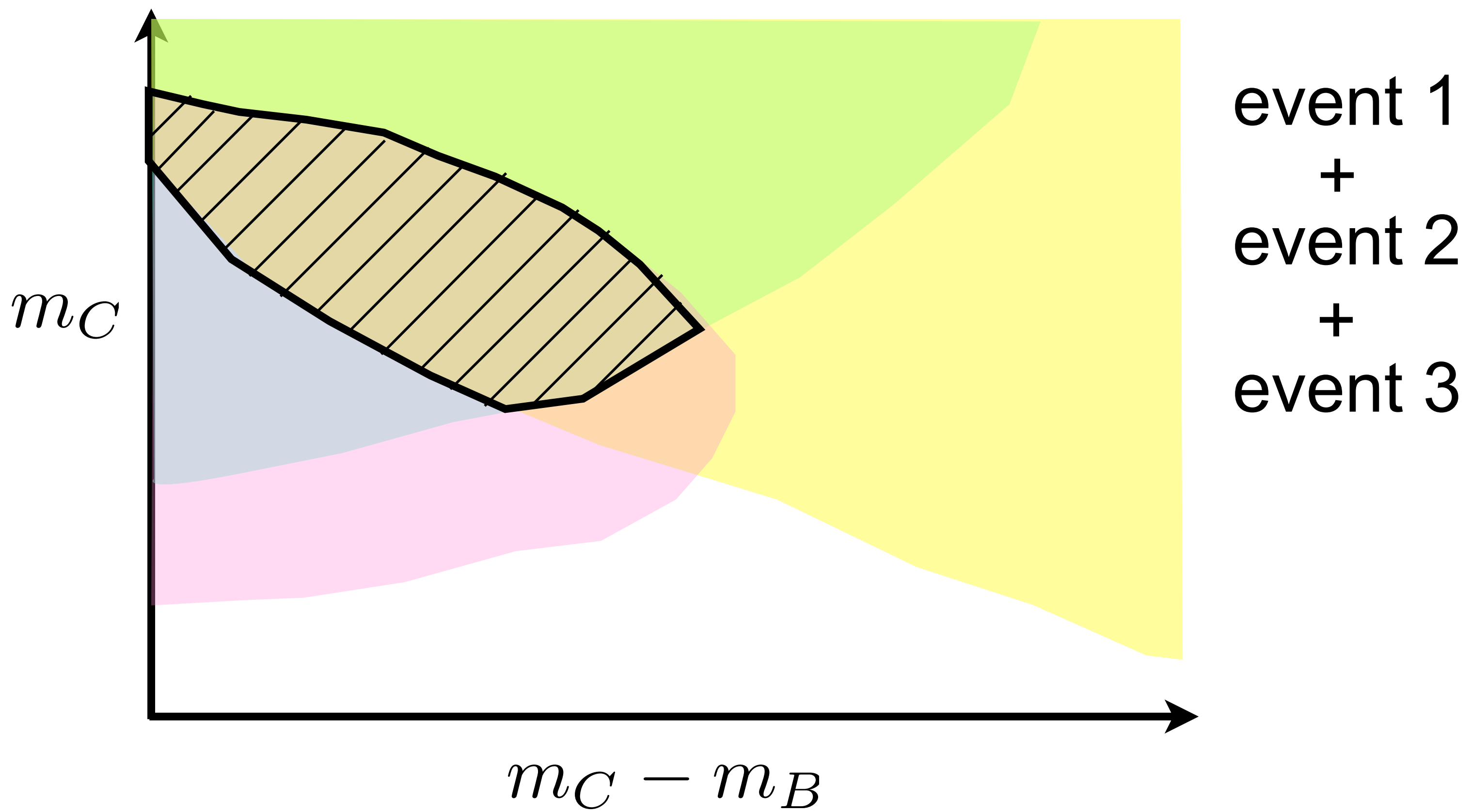
- Event by event allowed region



# Under constrained decay chains

H-C.Cheng, J.F.Gunion, Z.Han, G.Marandella, B.McElrath '07

- Event by event allowed region

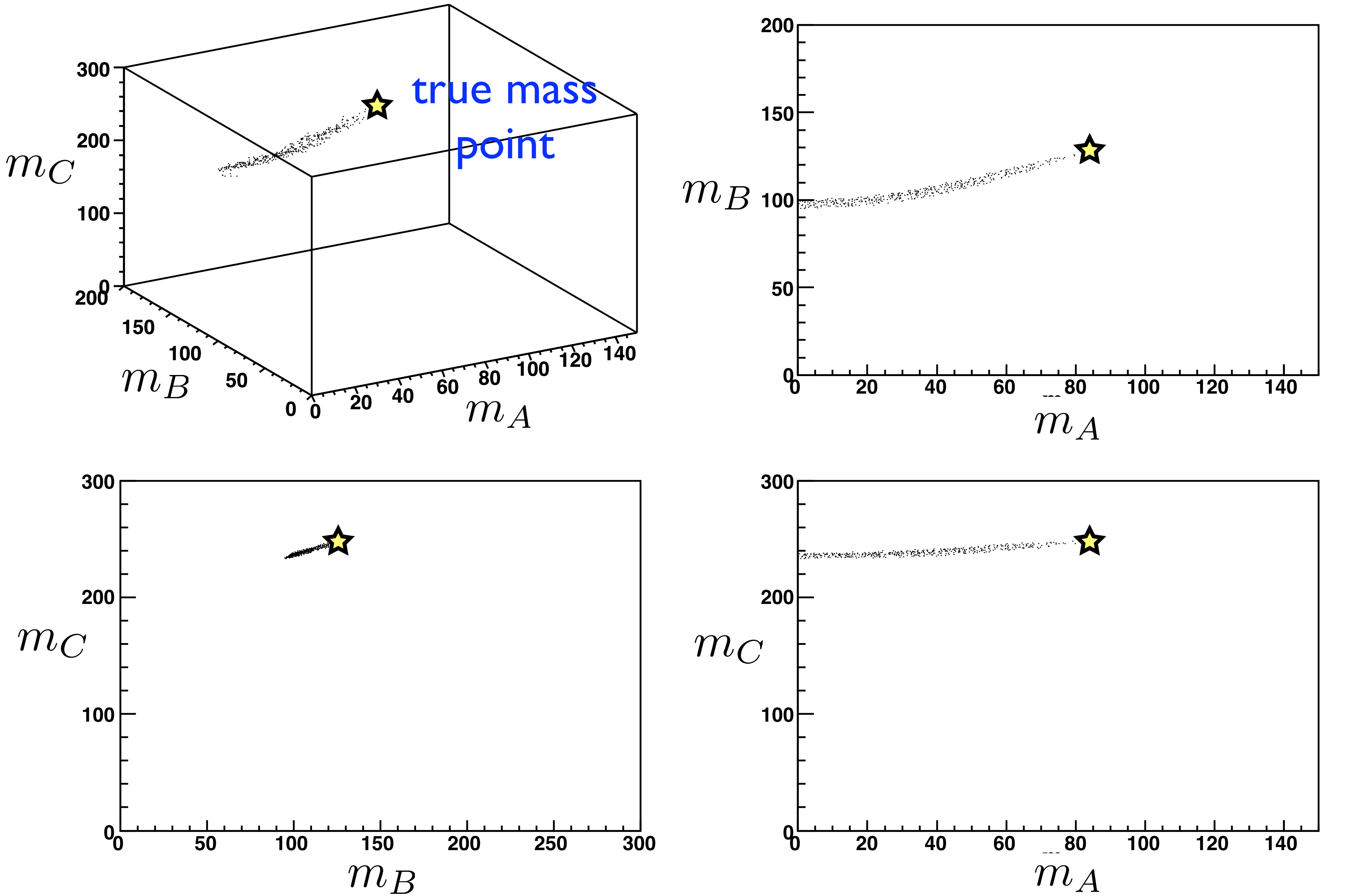



**We can combine all arrowed regions and obtain best constraint on the mass space.**

# Under constrained decay chains

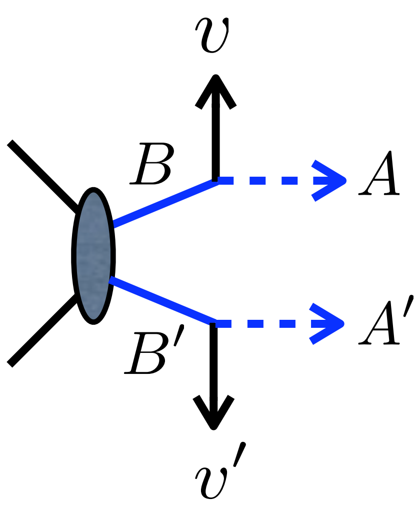
H-C.Cheng, J.F.Gunion, Z.Han, G.Marandella, B.McElrath '07

500 events (parton level)



# Shortest decay chains and mT2

H-C.Cheng, Z.Han '08




-- Constraints --

$$m_B^2 = (p_v + p_A)^2$$

$$m_A^2 = (p_A)^2$$

+ [ for pA' ]

$$p_{T\text{miss}}^{x(y)} = p_A^{x(y)} + p_{A'}^{x(y)}$$

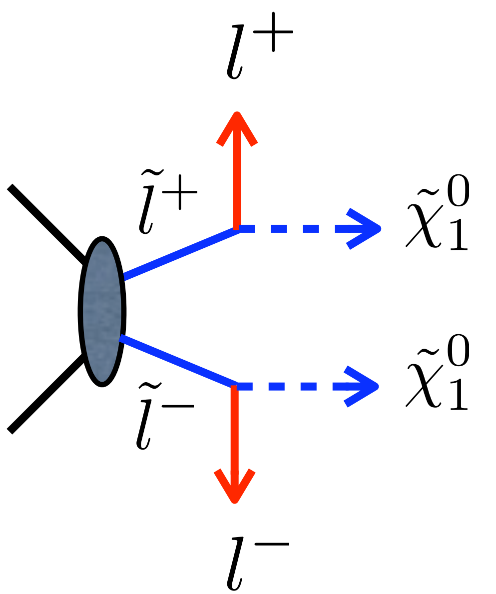
- One can get only mA dependent lower bound on mB, by scanning whole possible values of pA and pA' compatible with pTmiss constraints. This lower bound is known as mT2 variable.

$$m_B \geq m_{T2}(m_A)$$

C.G.Lester, D.J.Summers '99

$$= \min_{p_A, p_{A'}} \left[ \max \left\{ m_B(p_v, p_A), m_B(p_{v'}, p_A) \right\} \right] \Big|_{\mathbf{p}_{\text{miss}} = \mathbf{p}_A + \mathbf{p}_{A'}}$$

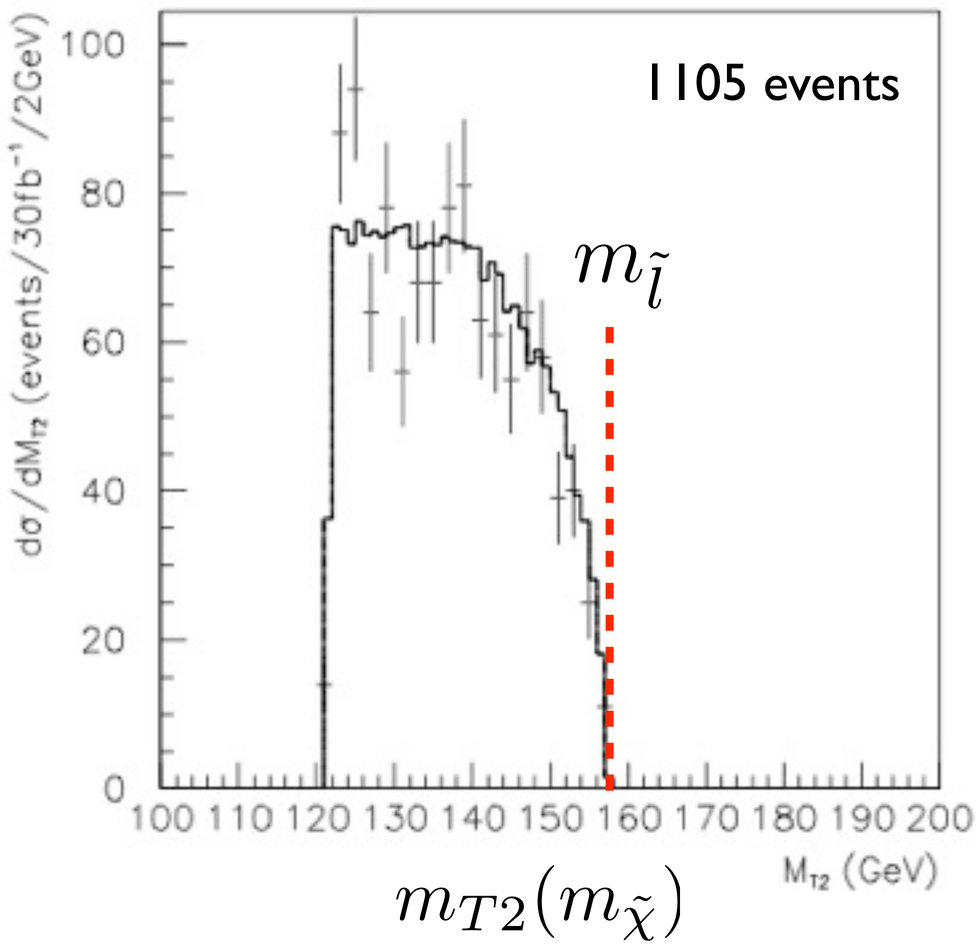
# mT2 distribution




$$m_{\tilde{l}} = 157.1\,\mathrm{GeV}$$

$$m_{\tilde{\chi}_1^0} = 121.5\,\mathrm{GeV}$$

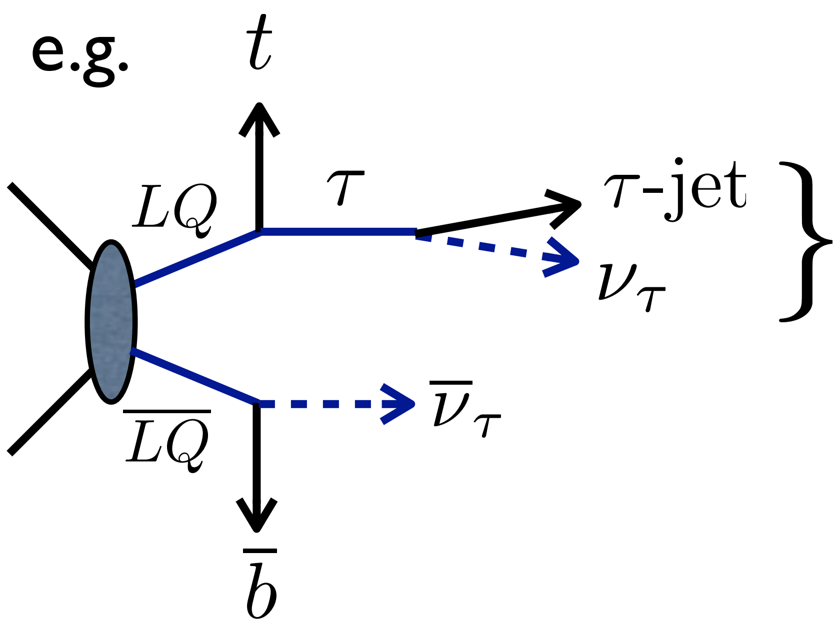
C.G.Lester, D.J.Summers '99



# More constraints

• If we have extra information on missing momenta or masses, we can easily incorporate it as constraints in scanning. Then we can get a better lower bound on the mass.

e.g.




$\nu_\tau$ is collimated to $\tau$-jet

$$p_{\nu_\tau} = E_{\nu_\tau}(1, \sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

constrained by $\tau$-jet direction

B.Gripaios, A.Papaefstathiou, K.S, B.Webber '10

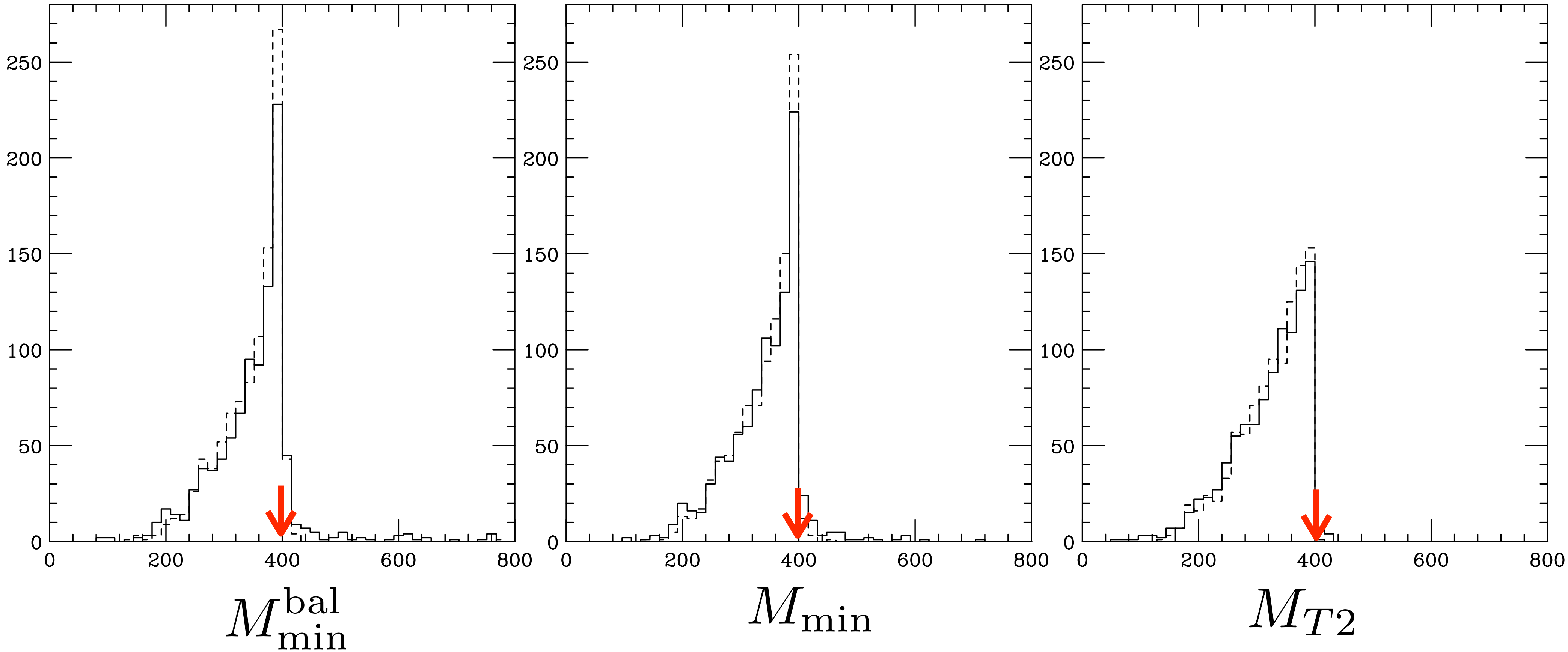
$$M_{T2} \leq M_{\rm min} \equiv \min[\max\{m_{t\tau}, m_{b\nu}\}]\Big|_{\substack{p_{\nu_\tau} \propto p_{\tau \rm jet} \\ \mathbf{p}_{\rm miss} = \mathbf{p}_\nu + \mathbf{p}_{\overline{\nu}}}}$$

$$\leq M_{\rm min}^{\rm bal} \equiv \min[m_{b\nu}]\Big|_{\substack{p_{\nu_\tau} \propto p_{\tau \rm jet}\ ,\ m_{b\nu} = m_{t\tau} \\ \mathbf{p}_{\rm miss} = \mathbf{p}_\nu + \mathbf{p}_{\overline{\nu}}}}$$

# Third generation Leptoquark

- 1000 events of leptoquark pair production with $M_{LQ}$ = 400 GeV
- solid line: $LQ\,\overline{LQ} \to \bar{b}\bar{\nu}t\tau^{(*)}$ dashed line: $LQ\,\overline{LQ} \to t\bar{\nu}\bar{b}\tau^{(*)}$
- parton level

B.Gripaios, A.Papaefstathiou, K.S, B.Webber '10

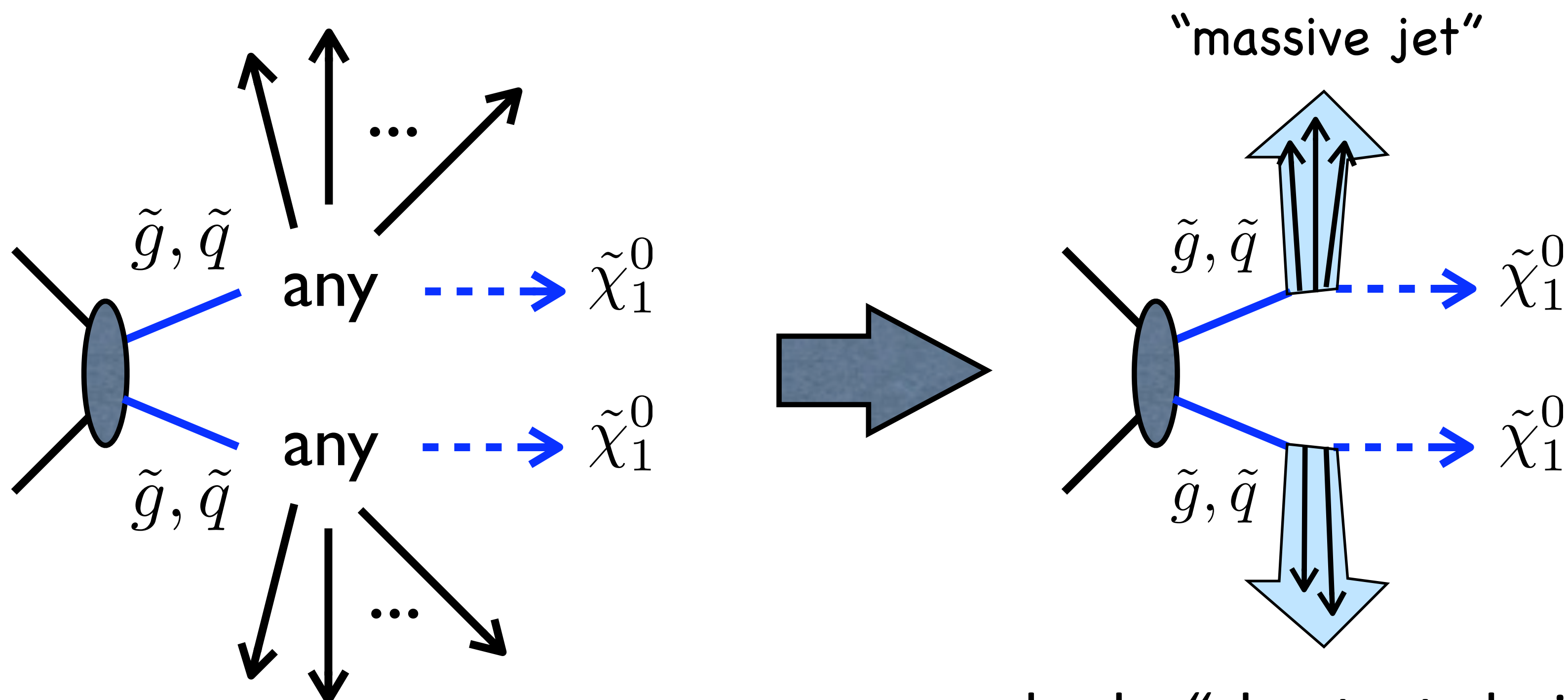


# For early stage of the LHC

*supersymmetry*

# Inclusive analysis

- low energy 7 TeV,  low luminosity L$\sim$1 fb$^{-1}$.
- do "inclusive" analysis

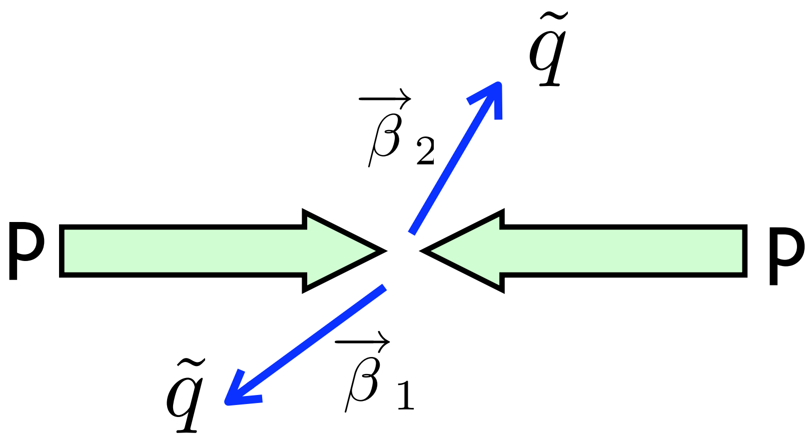


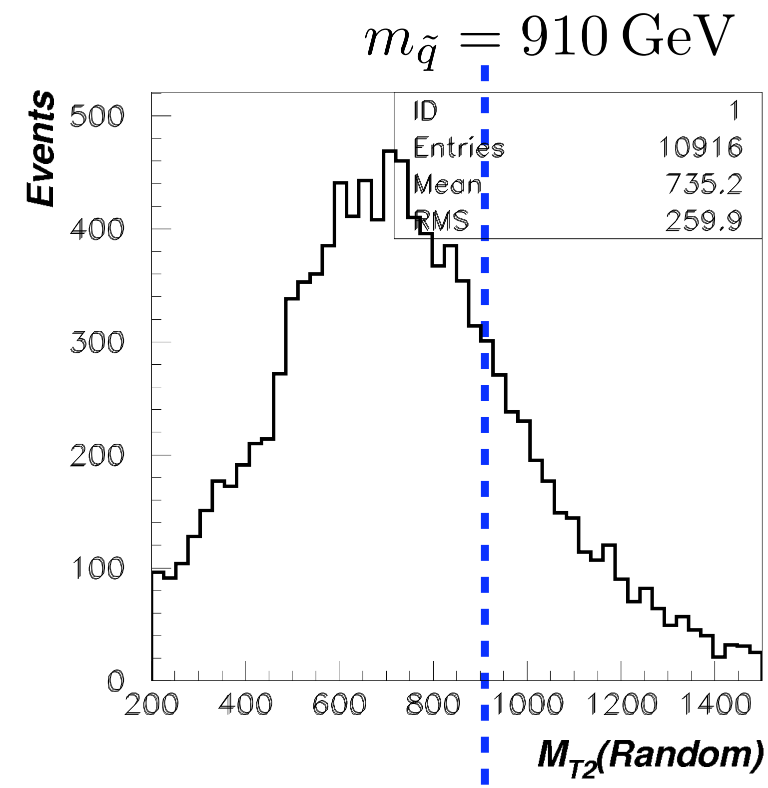

looks "shortest chains"

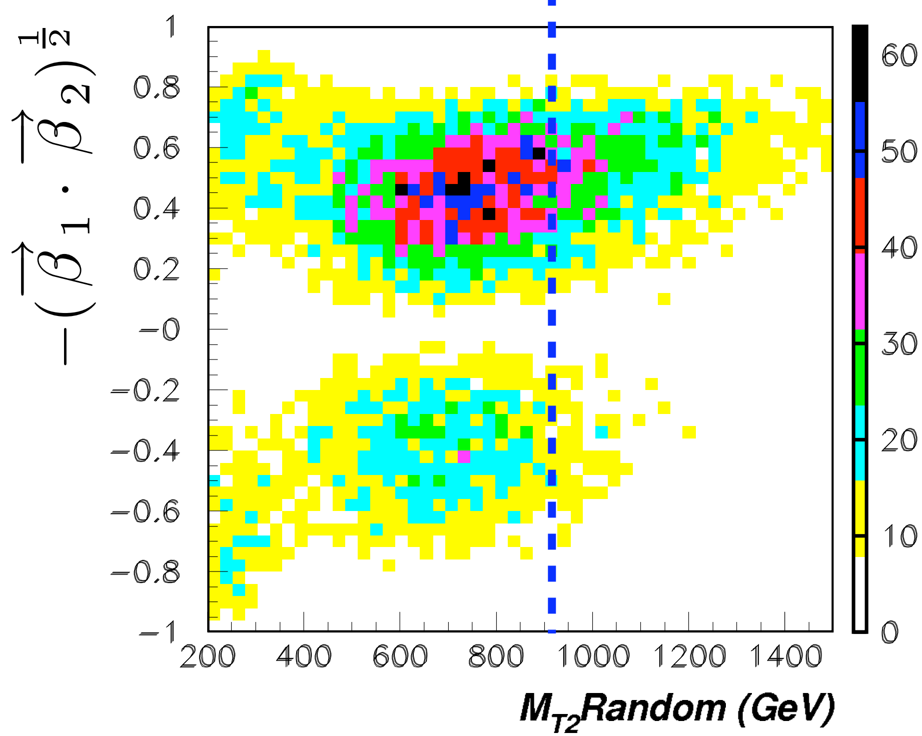
**use mT2 variable**

# How to group visible decay products into two massive jets?

- What if one separates them randomly?

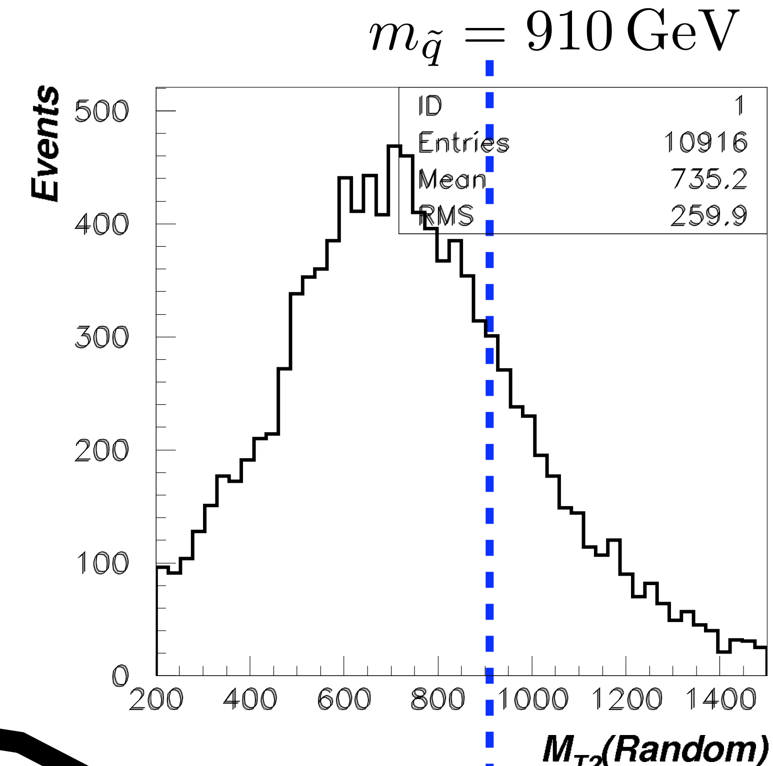


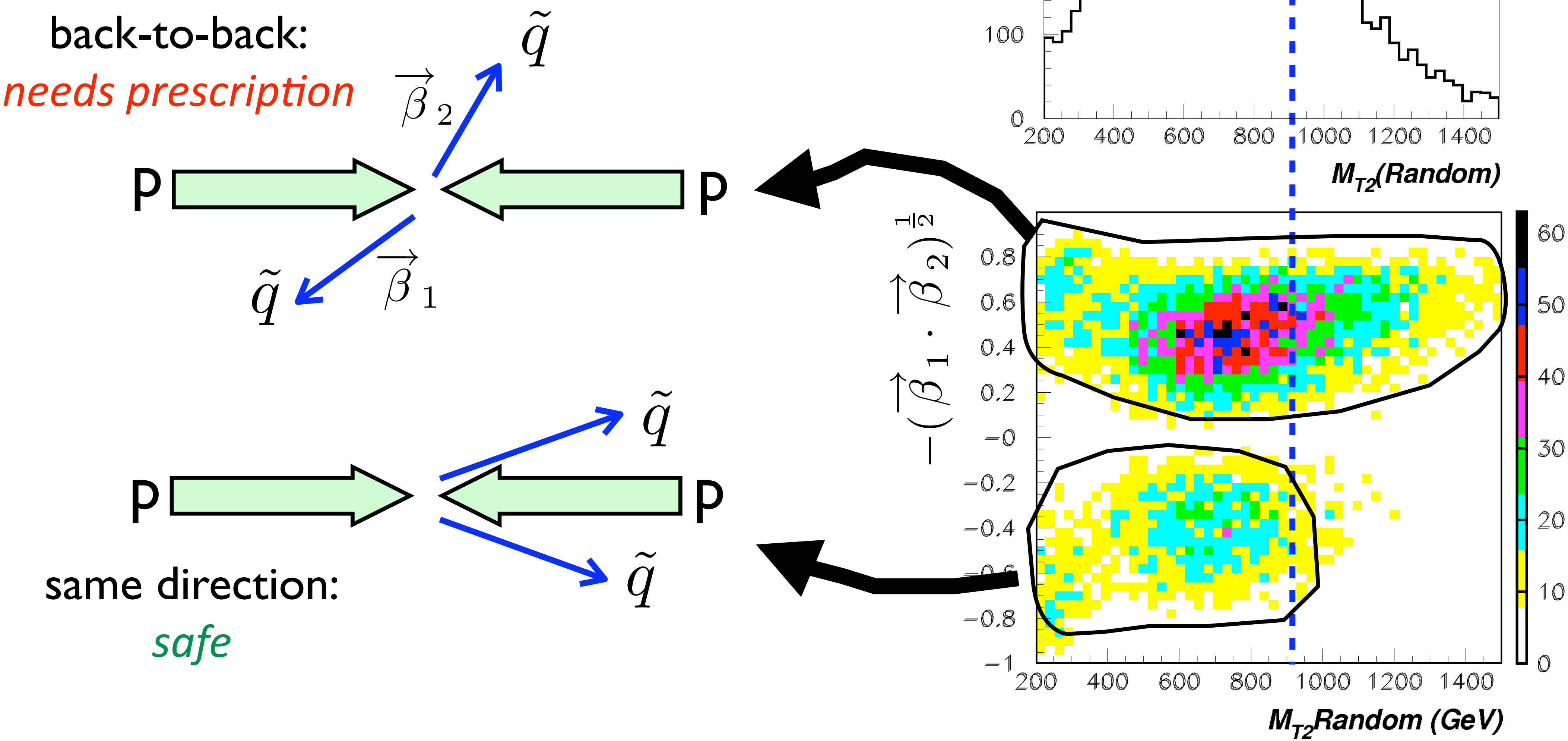



## How to separate decay products into two massive jets?

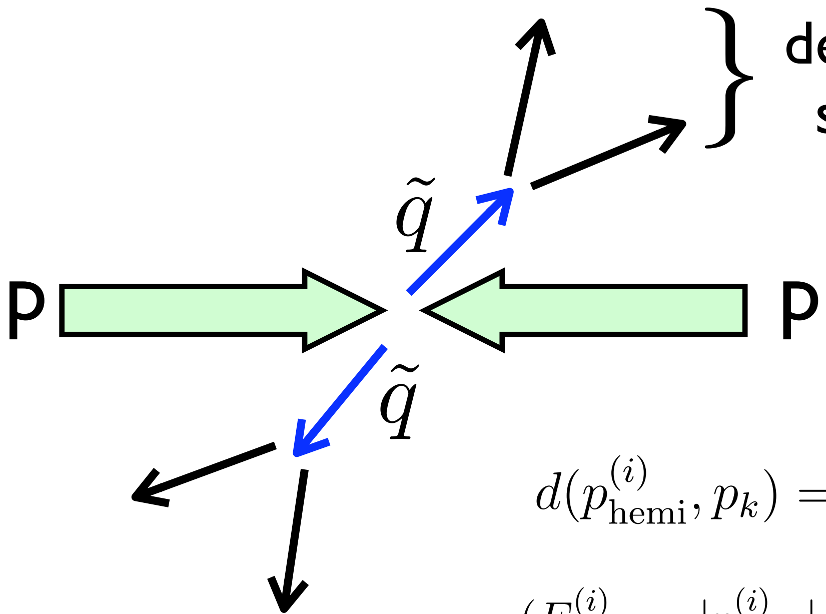
- What if one separates them randomly?



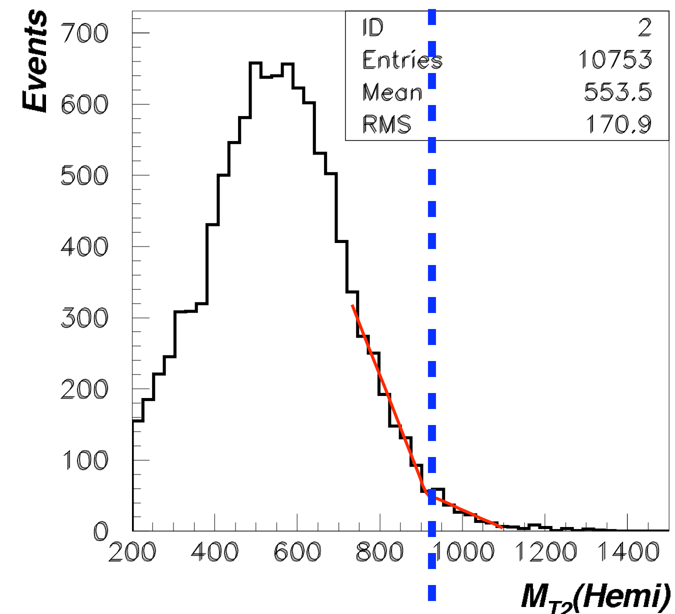
# Hemisphere algorithm

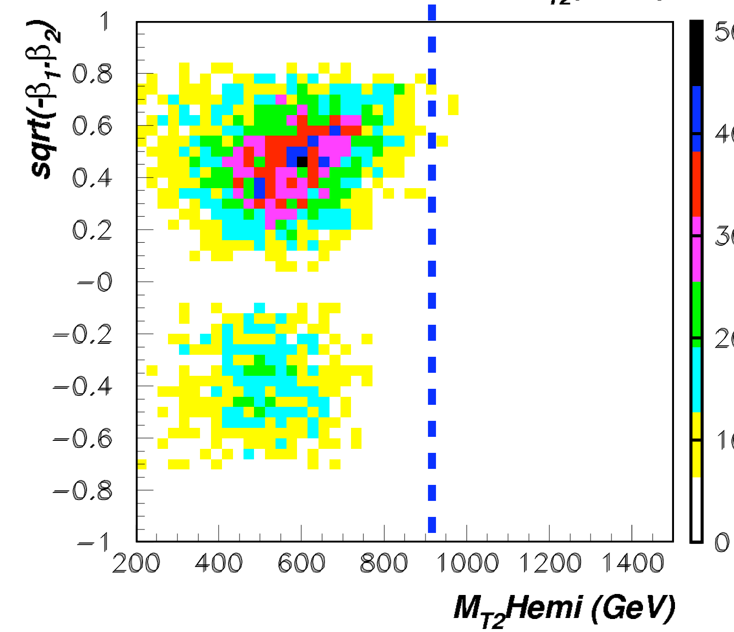
F.Moortgat, L.Pape '06




$$d(p^{(i)}_{\text{hemi}}, p_k) =$$

$$(E^{(i)}_{\text{hemi}} - |p^{(i)}_{\text{hemi}}| \cos\theta_{ik}) \frac{E^{(i)}_{\text{hemi}}}{(E^{(i)}_{\text{hemi}} + E_k)^2}$$




## Algorithm:

1. take two seeds.
seed 1 = highest pT object,
seed 2 = object i with largest pT×ΔR(1,i)

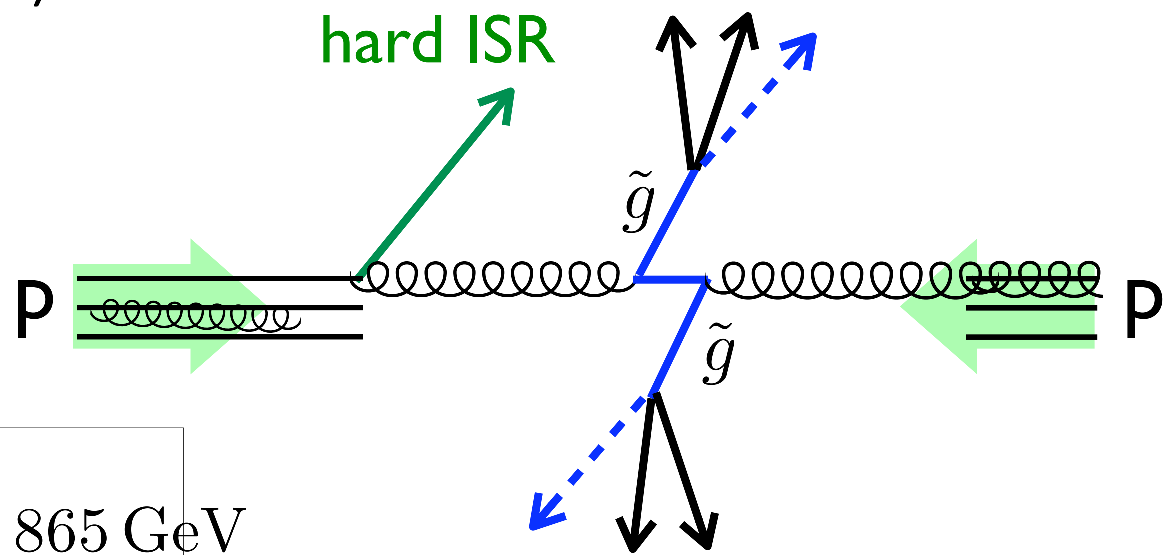
2. if d(1,i) < d(2,i) for object i, put i into hemisphere 1. Same for hemisphere 2.

3. define $p_{\text{hemi}}(i)$ as the momentum sum of all object assigned in hemisphere i.

4. Repeat 2 and 3 until converge.

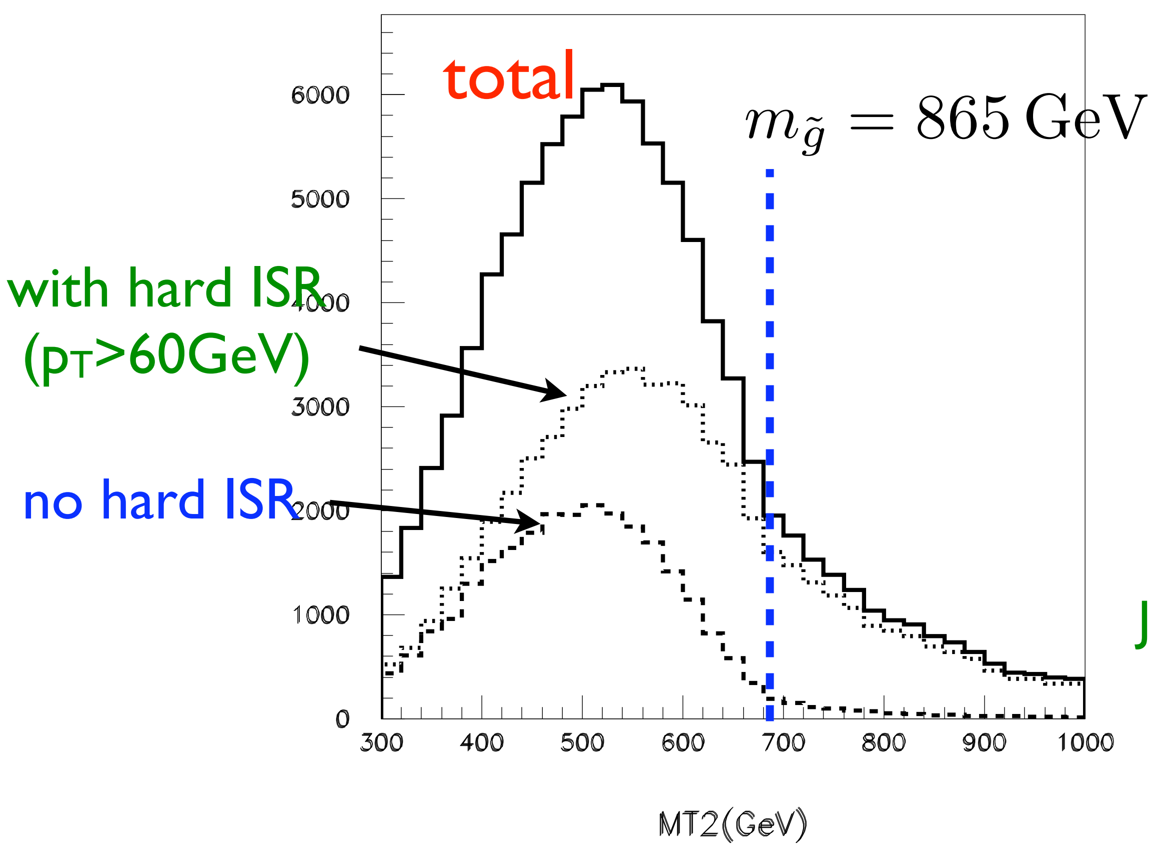
# ISR and gluino mass

- In gluino mass measurement, mT2 distribution is contaminated by a hard jet from initial state radiation (ISR).




$10^5$ events of

$$pp \to \tilde{g}\tilde{g}X \to jjjj\tilde{\chi}_1^0\tilde{\chi}_1^0 X$$




cuts:

$|\eta| < 2.5$

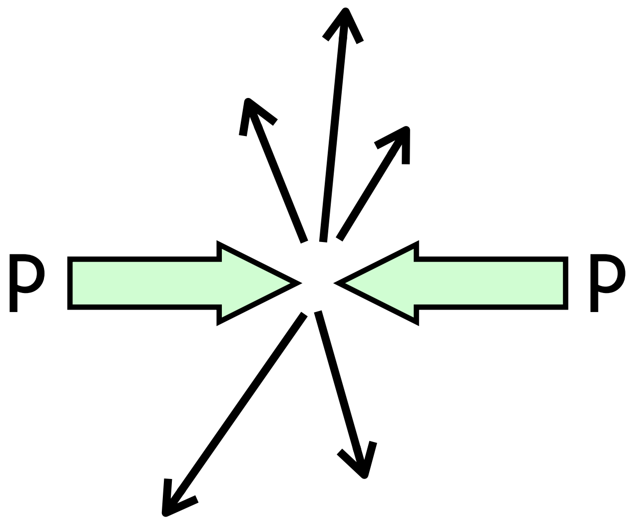
$p_T > 50\,\mathrm{GeV}$

J.Alwall, K.Hiramatsu, M.M.Nojiri, Y.Shimizu '09

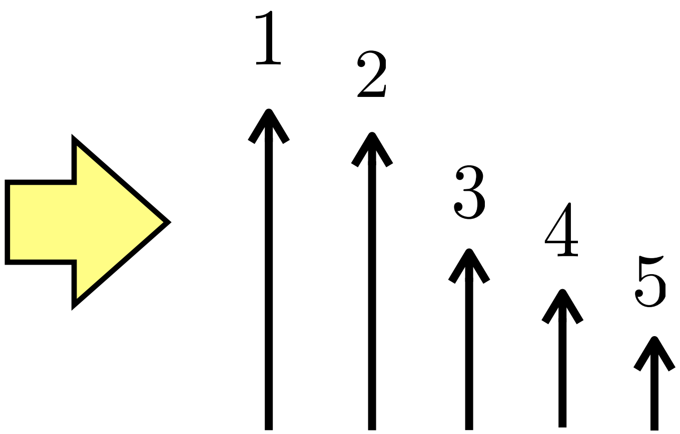
# Removing ISR

Is there ISR?

Which one is ISR?




$p_T$ ordered

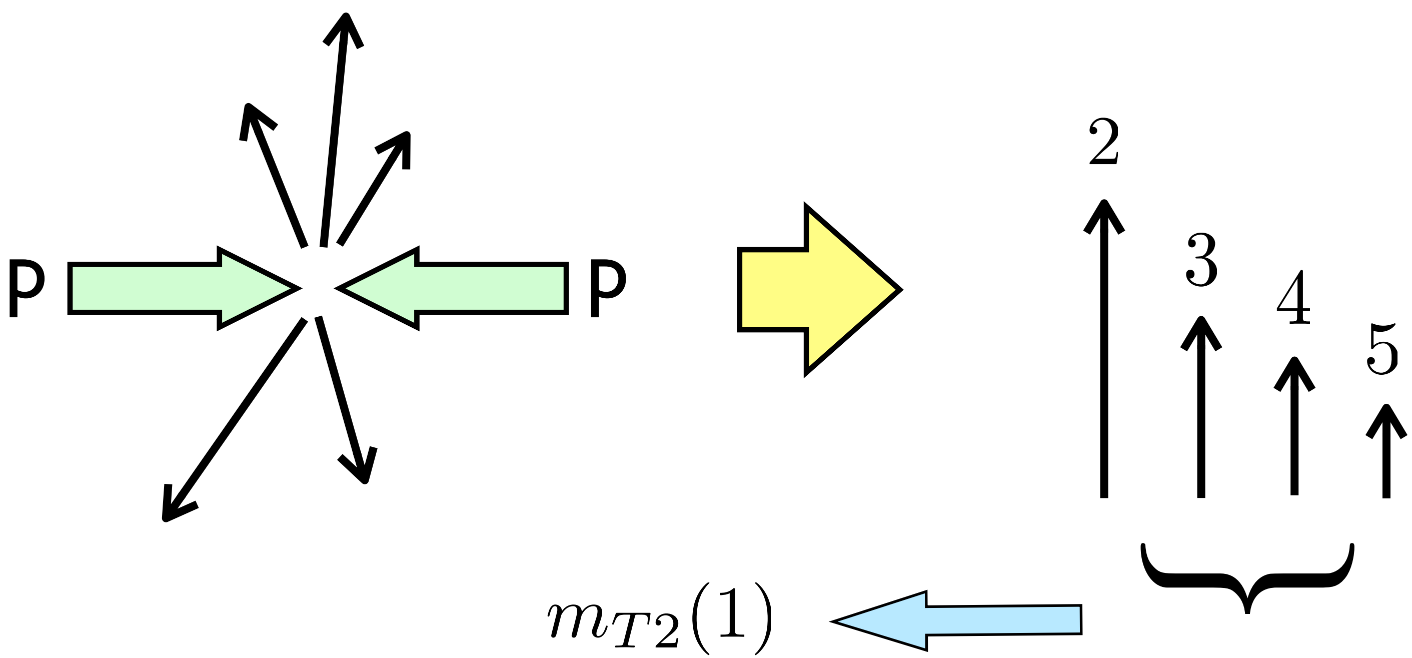


# Removing ISR

Is there ISR?

Which one is ISR?

$p_T$ ordered

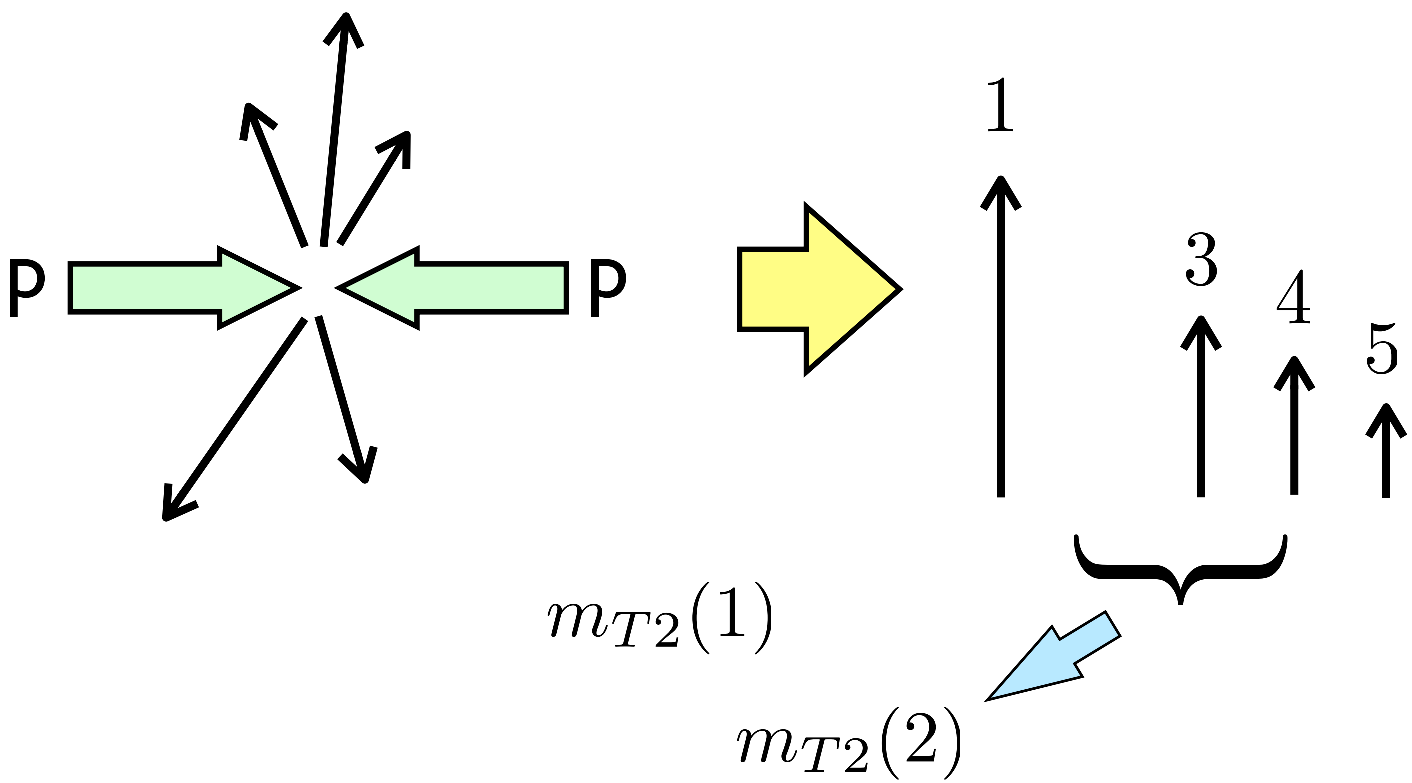


# Removing ISR

Is there ISR?

Which one is ISR?

$p_T$ ordered

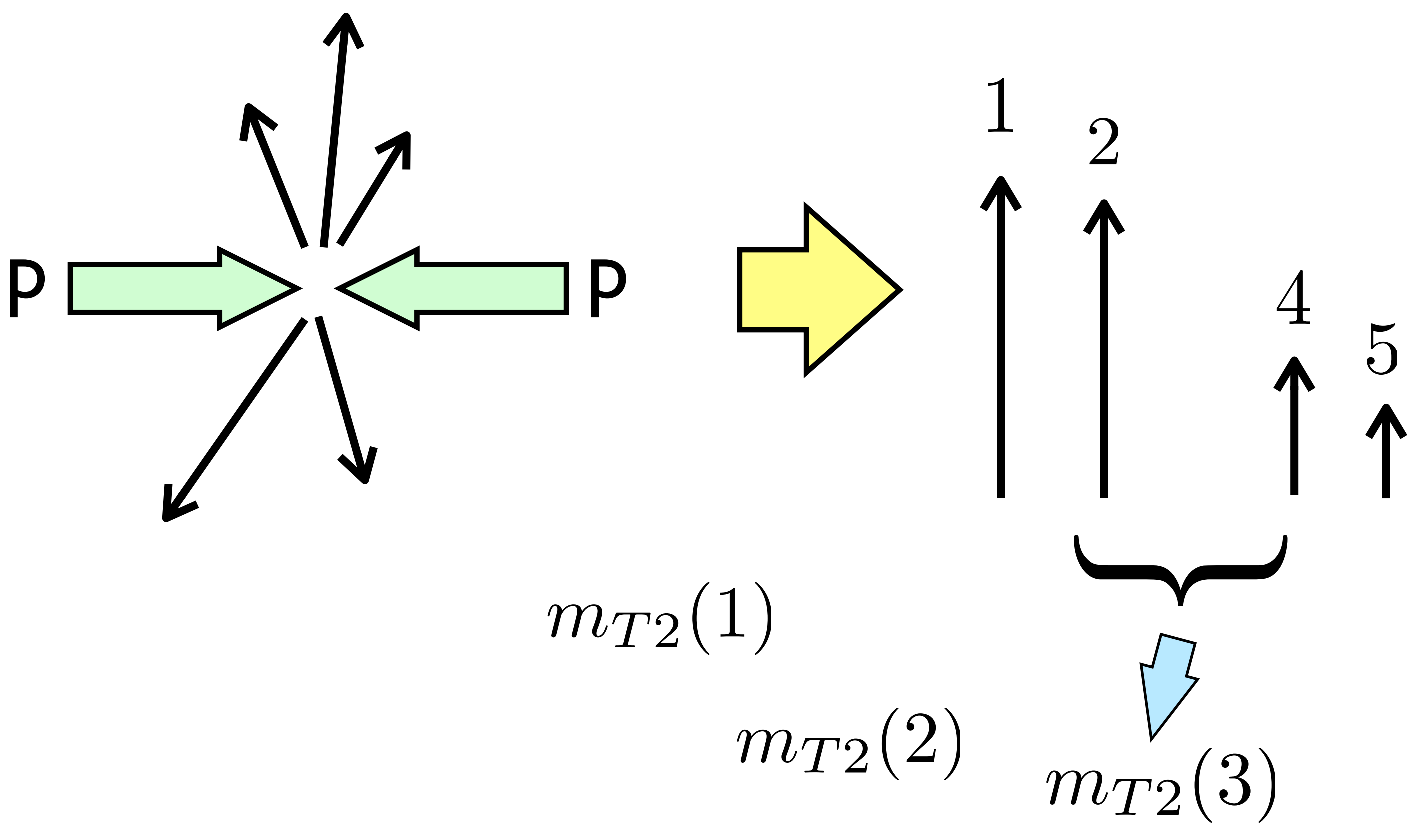


# Removing ISR

Is there ISR?

Which one is ISR?

$p_T$ ordered

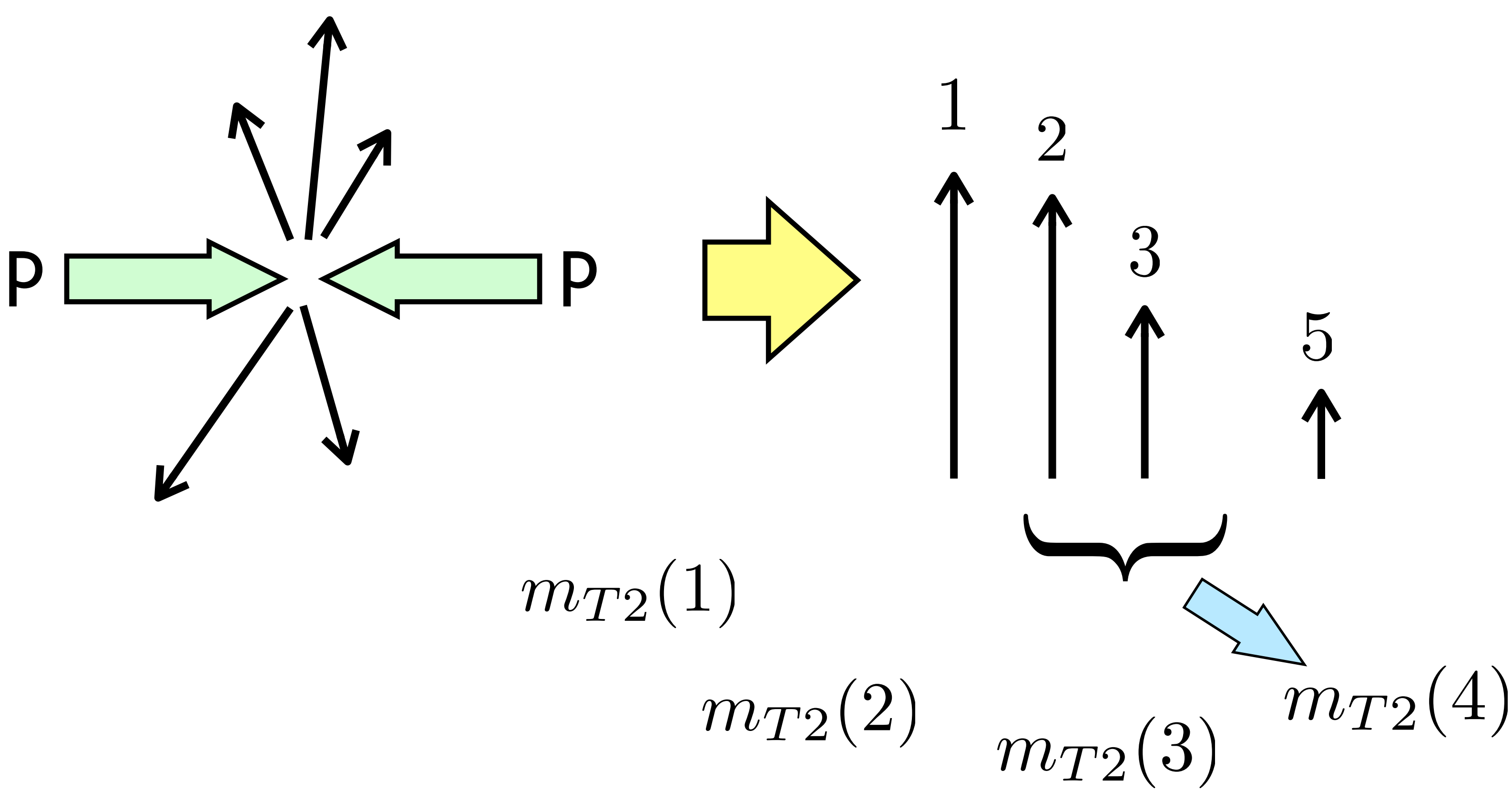


# Removing ISR

Is there ISR?

Which one is ISR?

$p_T$ ordered

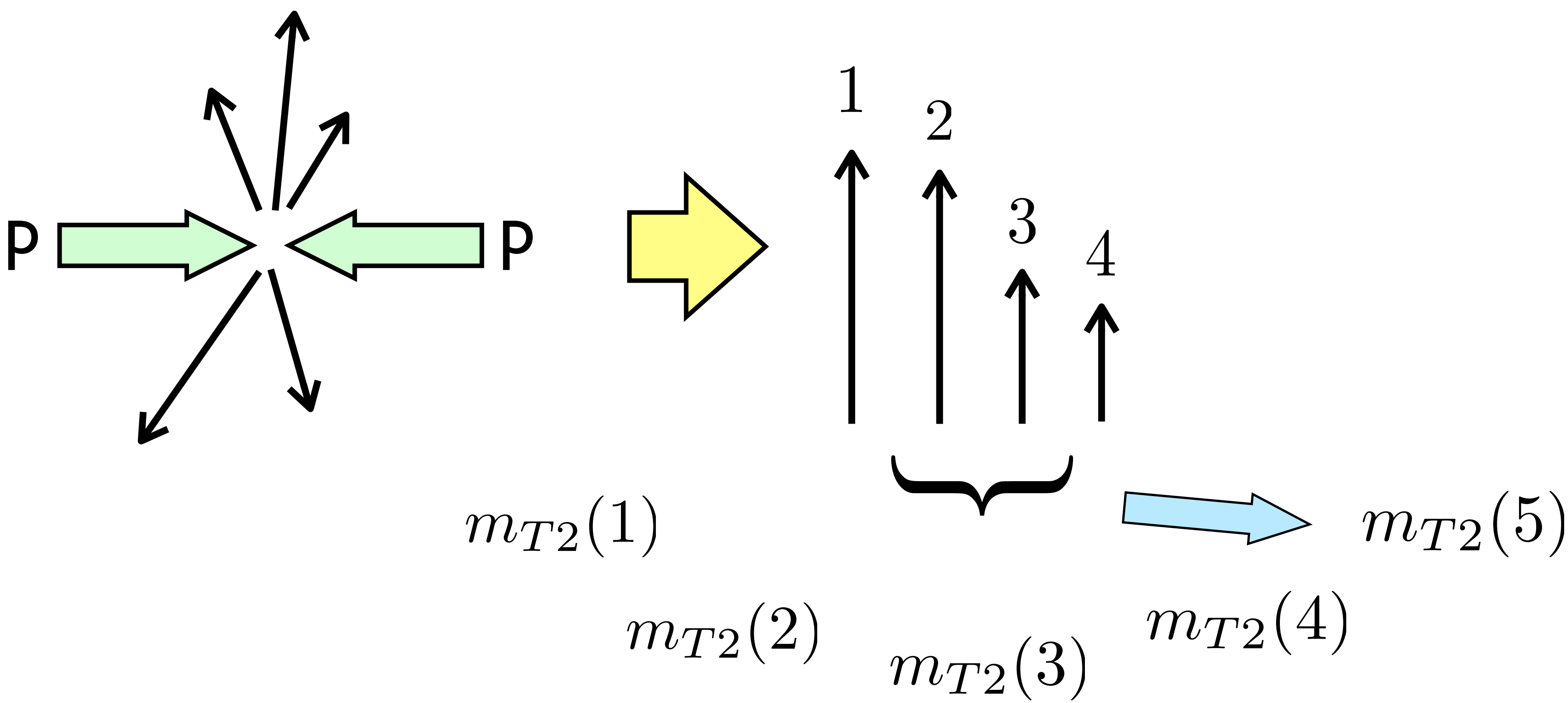


# Removing ISR

Is there ISR?

Which one is ISR?

$p_T$ ordered

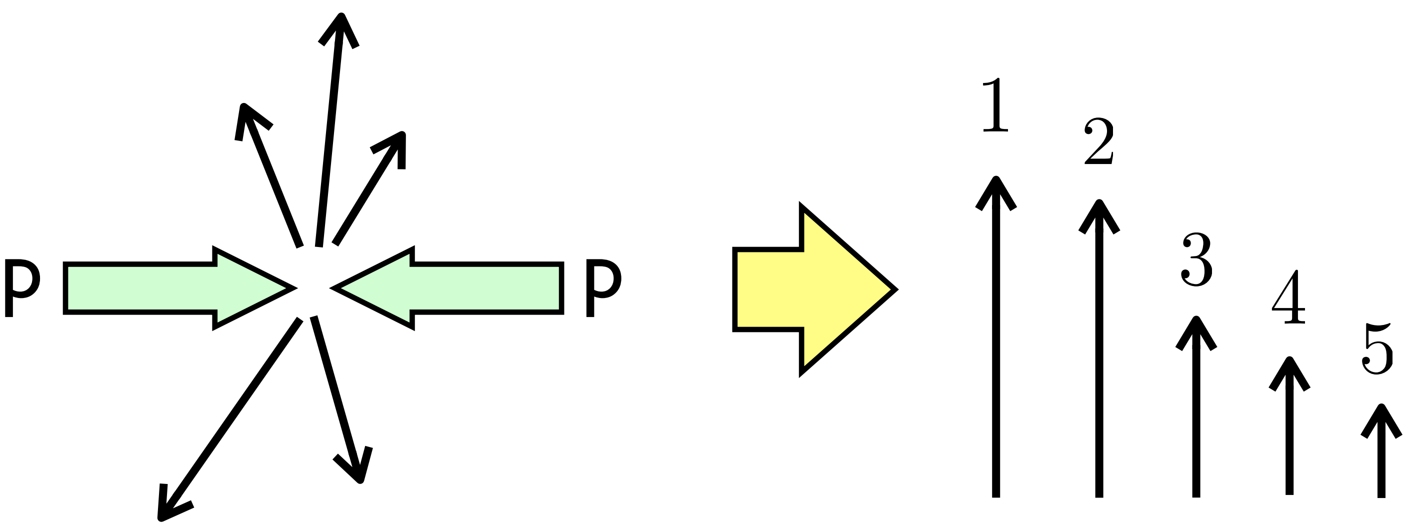


# Removing ISR

Is there ISR?

Which one is ISR?

$p_T$ ordered




$m_{T2}(1)$ $m_{T2}(2)$ $m_{T2}(3)$ $m_{T2}(4)$ $m_{T2}(5)$

$$m_{T2}^{\min} = \min_i [m_{T2}(i)]$$

**can get a safe lower bound on gluino mass by choosing smallest one**

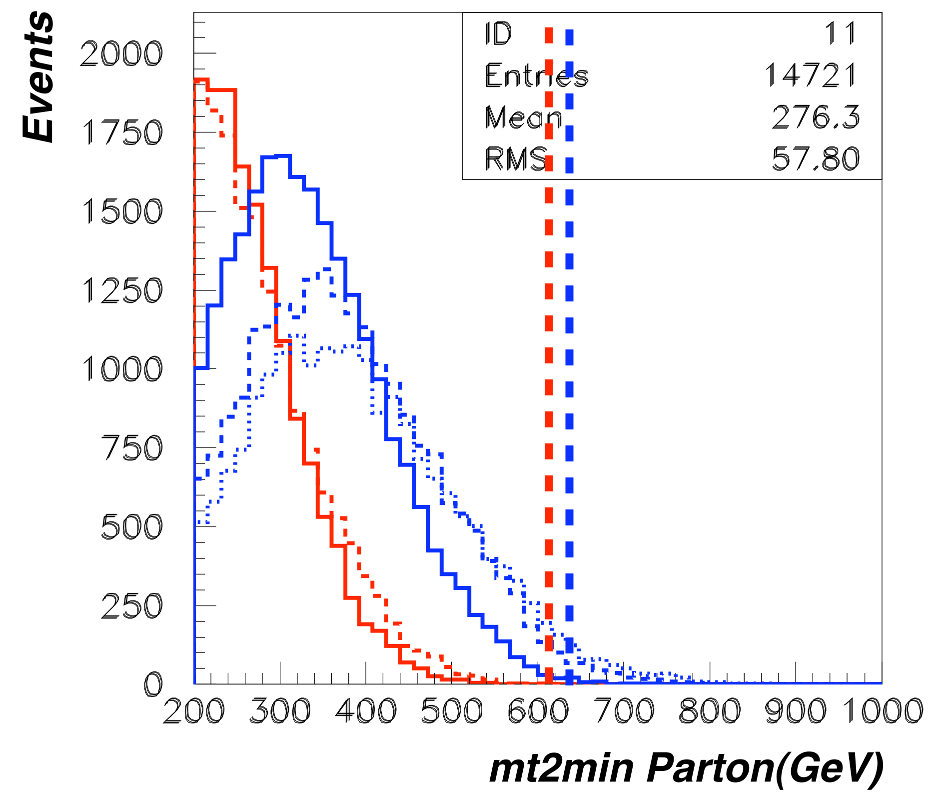
J.Alwall, K.Hiramatsu, M.M.Nojiri, Y.Shimizu '09

# $m_{T2}^{min}$ distribution

M.M.Nojiri, K.S '10

- Depending on mass spectra, $m_{T2}^{min}$ significantly underestimates gluino mass.

| | Point 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $m_0$ | 100 | 250 | 500 | 650 | 750 |
| $M_{1/2}$ | 250 | 250 | 250 | 250 | 250 |
| $m_{\tilde{g}}$ | 612 | 620 | 636 | 646 | 651 |
| $m_{\tilde{u}_L}$ | 560 | 602 | 734 | 837 | 913 |
| | red solid | red dashed | blue solid | blue dashed | blue dotted |



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M.M.Nojiri, K.S '10

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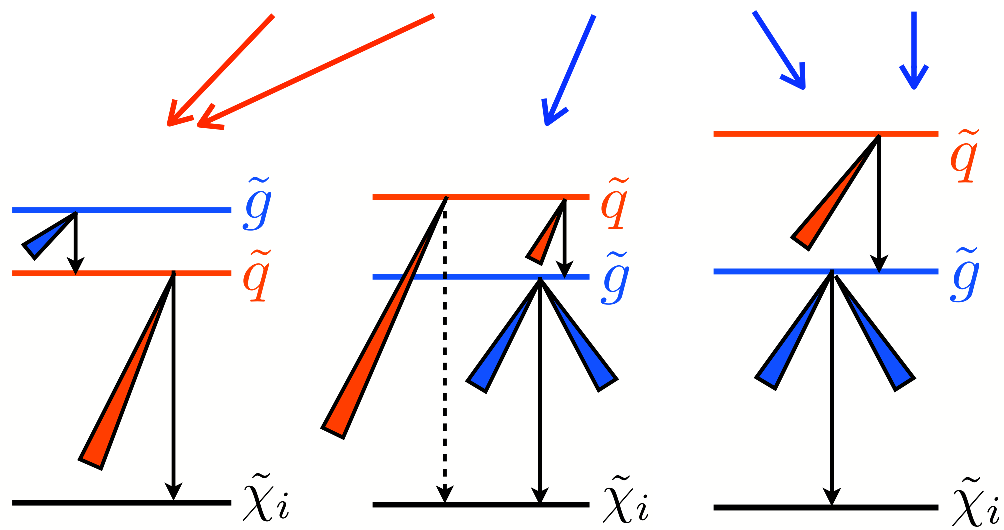
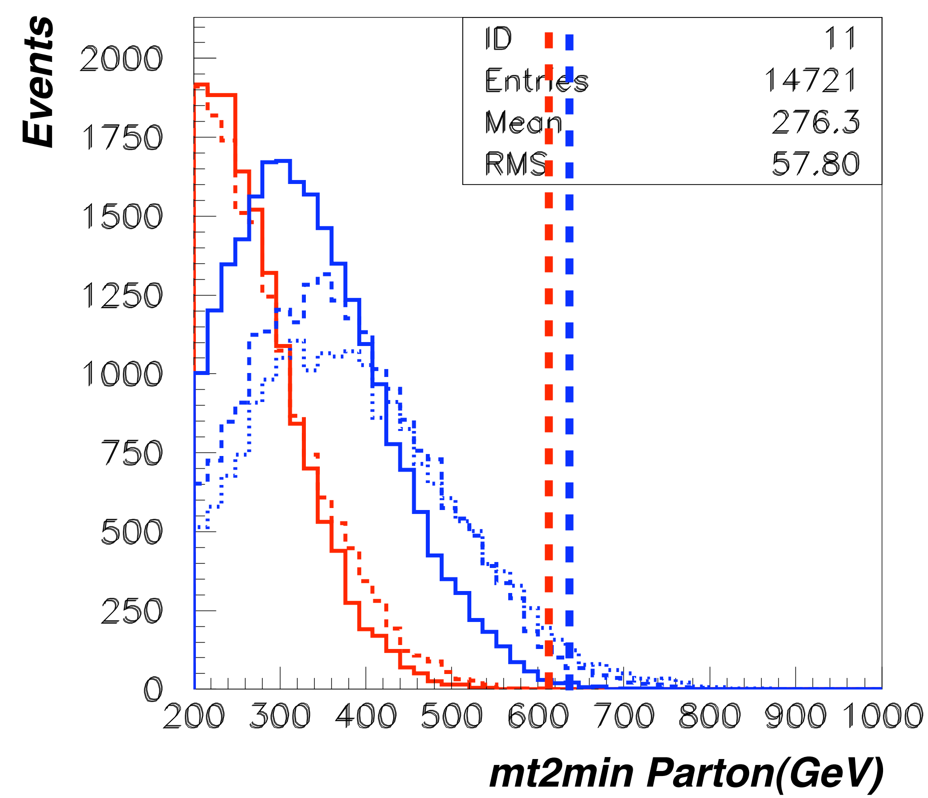
| $m_{\tilde{u}_L}$ | 560 | 602 | 734 | 837 | 913 |
| | red solid line | red dashed line | blue solid line | blue dashed line | blue dotted line |



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M.M.Nojiri, K.S '10

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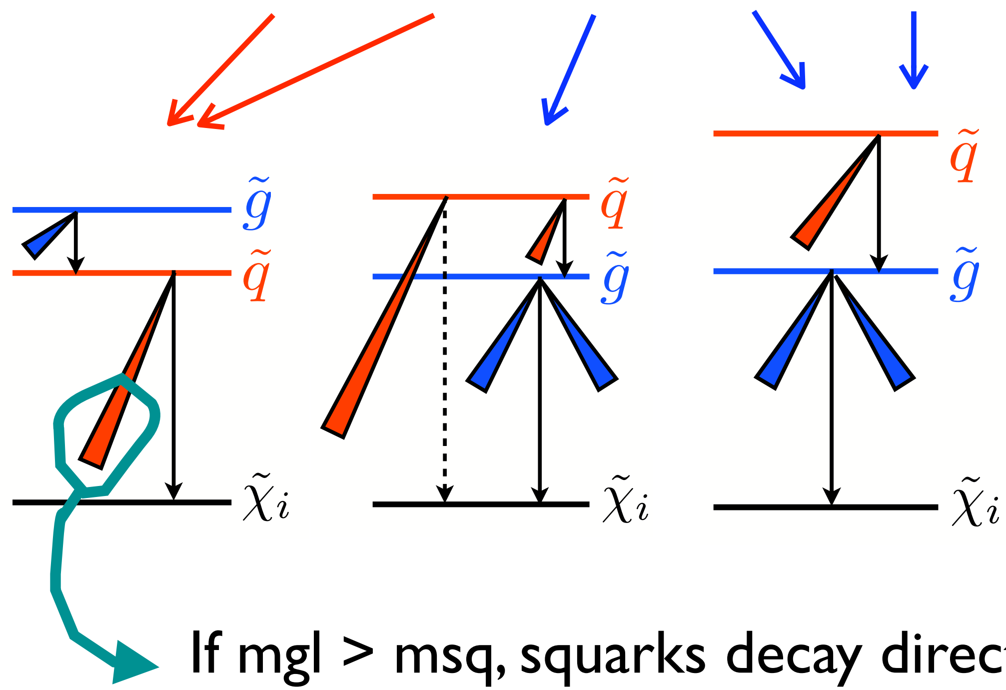
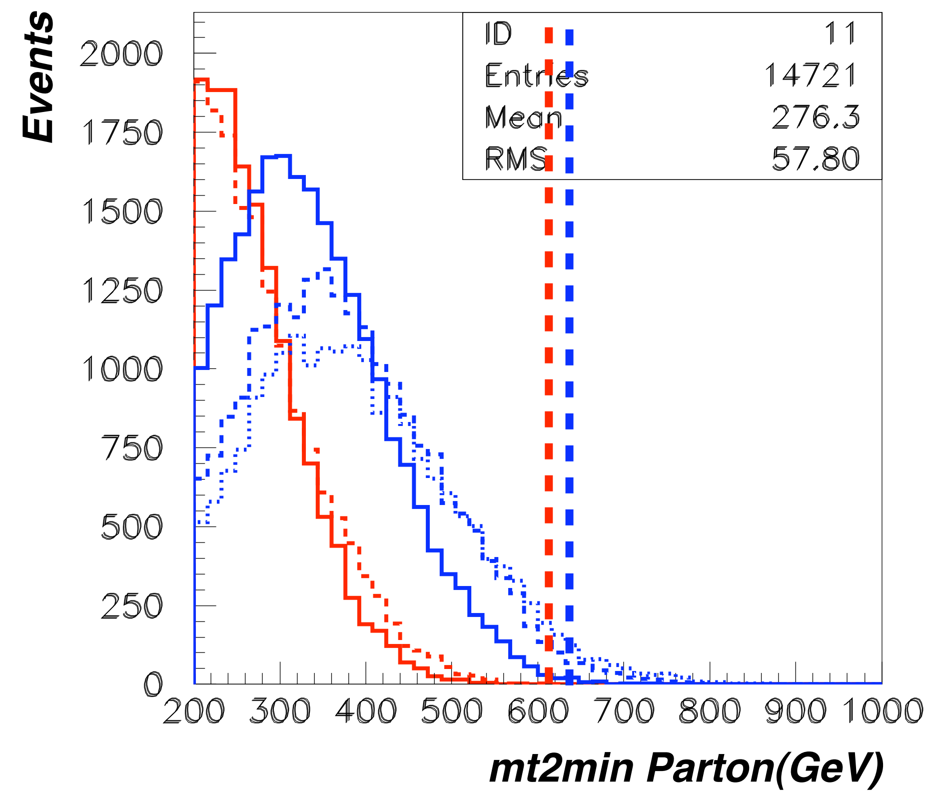
| | —— | - - - | —— | - - - | · · · · |



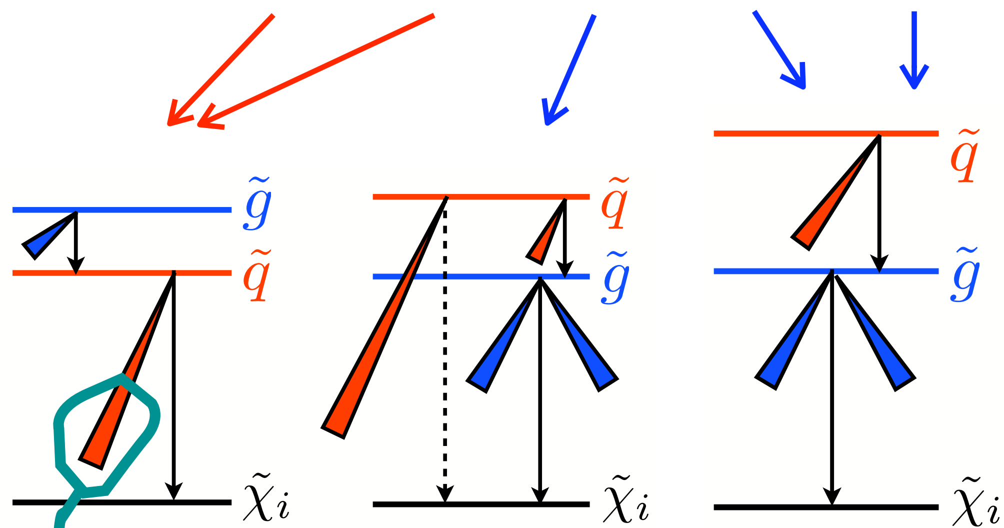




If mgl > msq, squarks decay directly to weak gauginos producing a hard jet. Two highest jets often come from squark decay (not ISR) and if one removes one of them, $m_{T2}^{min}$ significantly underestimates gluino mass.

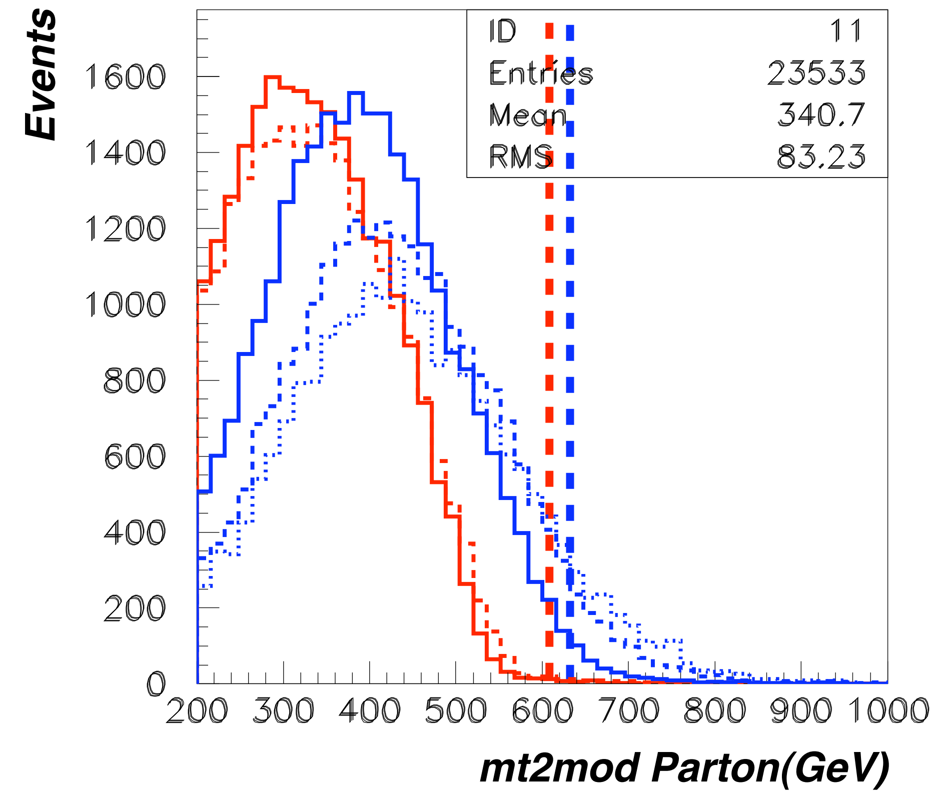
# $m_{T2}^{min}$(mod) distribution

- Depending on mass spectra, $m_{T2}^{min}$ significantly underestimates gluino mass.

| | Point 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $m_0$ | 100 | 250 | 500 | 650 | 750 |
| $M_{1/2}$ | 250 | 250 | 250 | 250 | 250 |
| $m_{\tilde{g}}$ | 612 | 620 | 636 | 646 | 651 |
| $m_{\tilde{u}_L}$ | 560 | 602 | 734 | 837 | 913 |
| | ——— | - - - | ——— | - - - | · · · · |



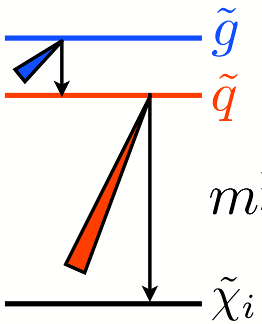

M.M.Nojiri, K.S. '10




To avoid this issue, we should keep two highest jets in calculation of $m_{T2}^{min}$ in mgl > msq spectrum.

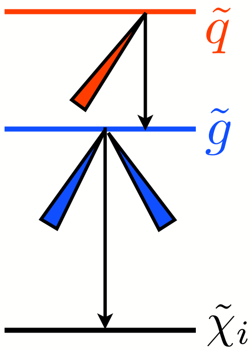
$$m_{T2}^{min}(\text{mod}) \equiv \min_{i \neq 1,2} [m_{T2}(i)]$$

# $m_{T2}^{min}$ or $m_{T2}^{min}$(mod) ?




mgl > msq

$$m_{T2}^{\min}(\text{mod}) \equiv \min_{i \neq 1,2}[m_{T2}(i)]$$

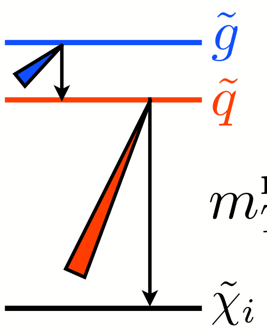



msq > mgl

$$m_{T2}^{\min} = \min_{i}[m_{T2}(i)]$$

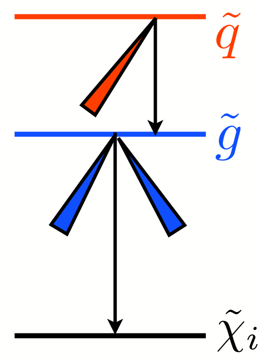
How can we know?

# $m_{T2}^{min}$ or $m_{T2}^{min}$(mod) ?




mgl > msq

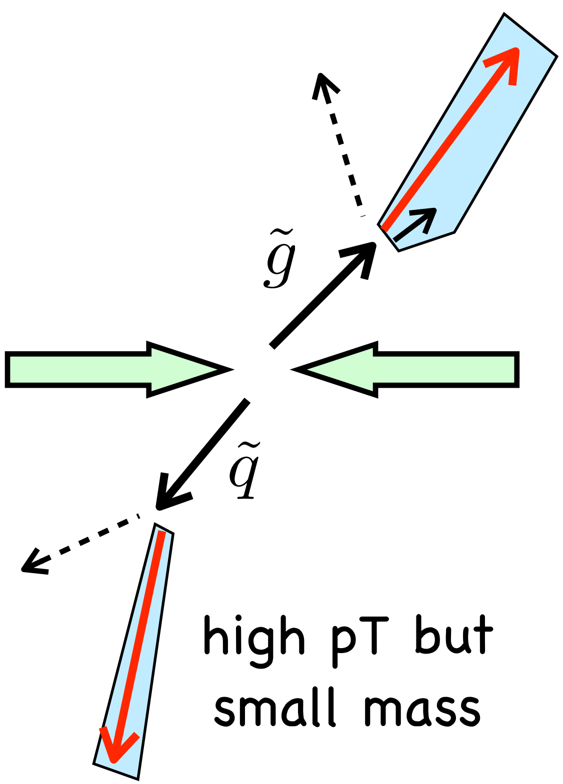
$$m_{T2}^{\min}(\mathrm{mod}) \equiv \min_{i\neq 1,2}[m_{T2}(i)]$$

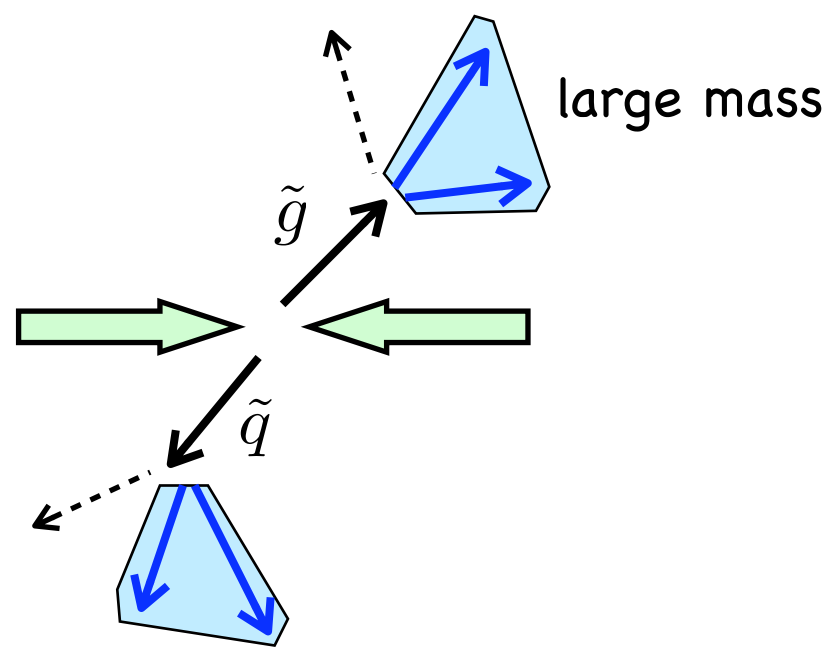



msq > mgl

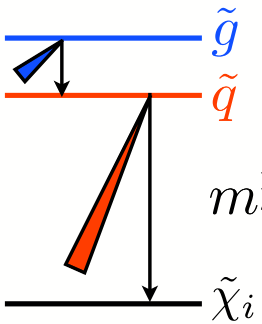
$$m_{T2}^{\min} = \min_{i}[m_{T2}(i)]$$

## How can we know?



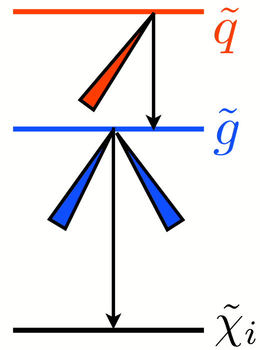



# $m_{T2}^{min}$ or $m_{T2}^{min}$(mod) ?




mgl > msq

$$m_{T2}^{\rm min}({\rm mod}) \equiv \min_{i \neq 1,2} [m_{T2}(i)]$$



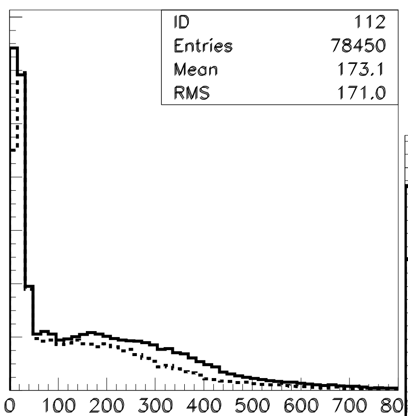

msq > mgl

$$m_{T2}^{\rm min} = \min_{i} [m_{T2}(i)]$$

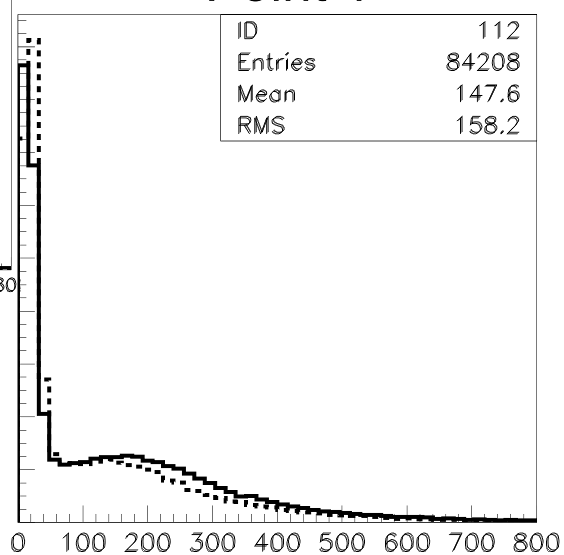
M.M.Nojiri, K.S '10

## Shape of hemisphere

Point 2



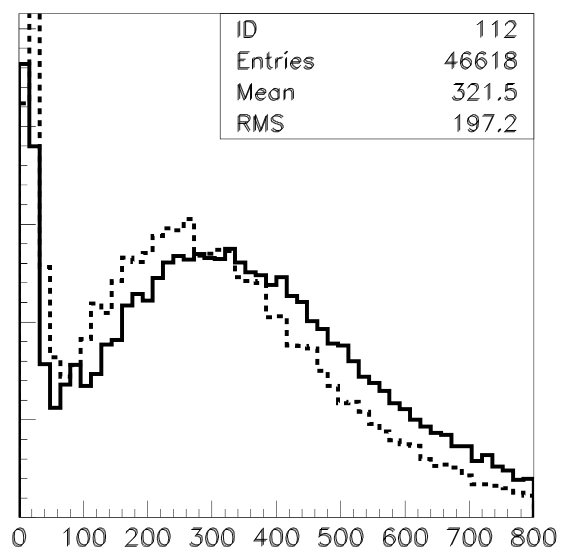

Point 1




$m_{\rm hemi}$ [GeV]

1 peak

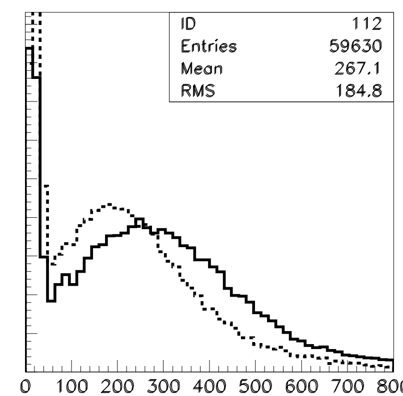
Point 5



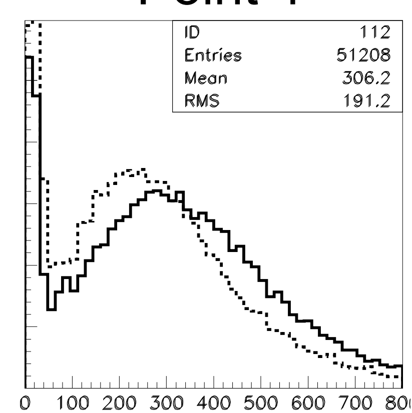

$m_{\rm hemi}$ [GeV]

2 peaks

Point 3

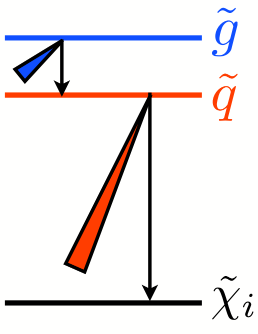



Point 4



# Squark mass

M.M.Nojiri, K.S '10



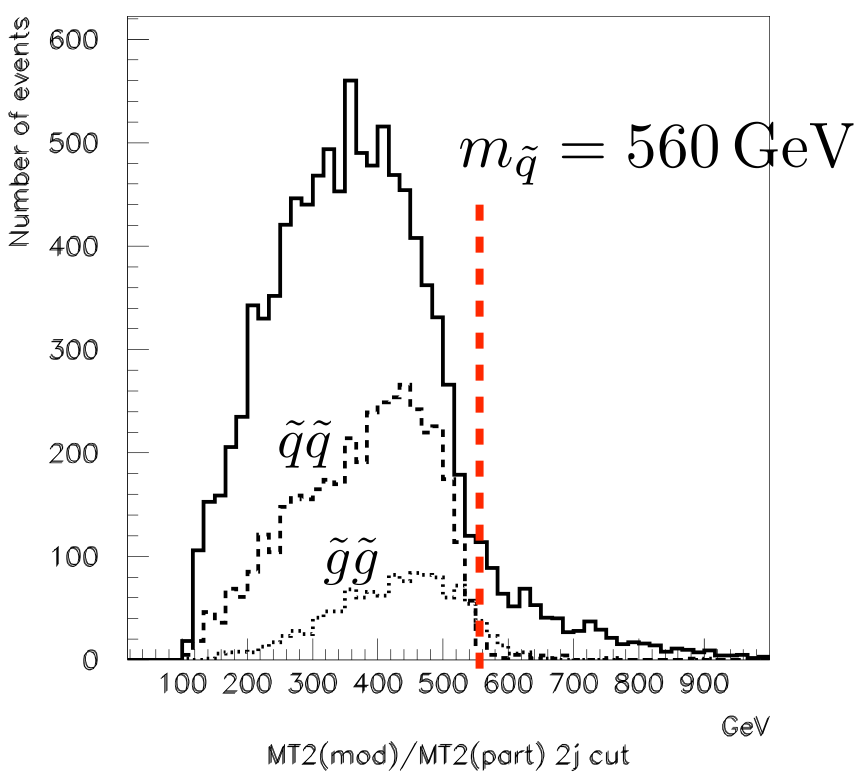

mgl > msq

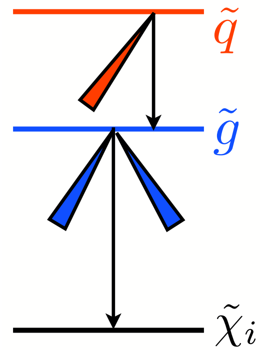
use $m_{T2}^{min}$(mod)

with cut:

2 jets with $p_T$>200 GeV

Point 1




msq > mgl

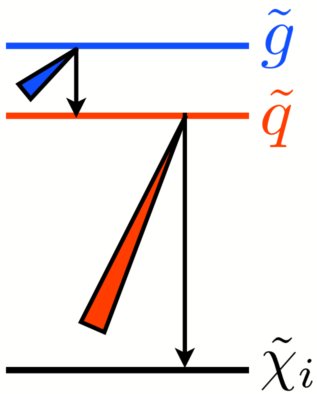
small ISR contamination

⇨ use mT2

# $E_{CM}$ = 7 TeV, L = 1 fb$^{-1}$

M.M.Nojiri, K.S '10

mgl > msq:




| | $m_0$ | $m_{1/2}$ | $m_{gluino}$ | $m_{squark}$(uL) |
|---|---|---|---|---|
| Point I' | 100 | 210 | 522 | 478 |

$m_{gluino}$ : $m_{T2}^{\min}(\mathrm{mod})$

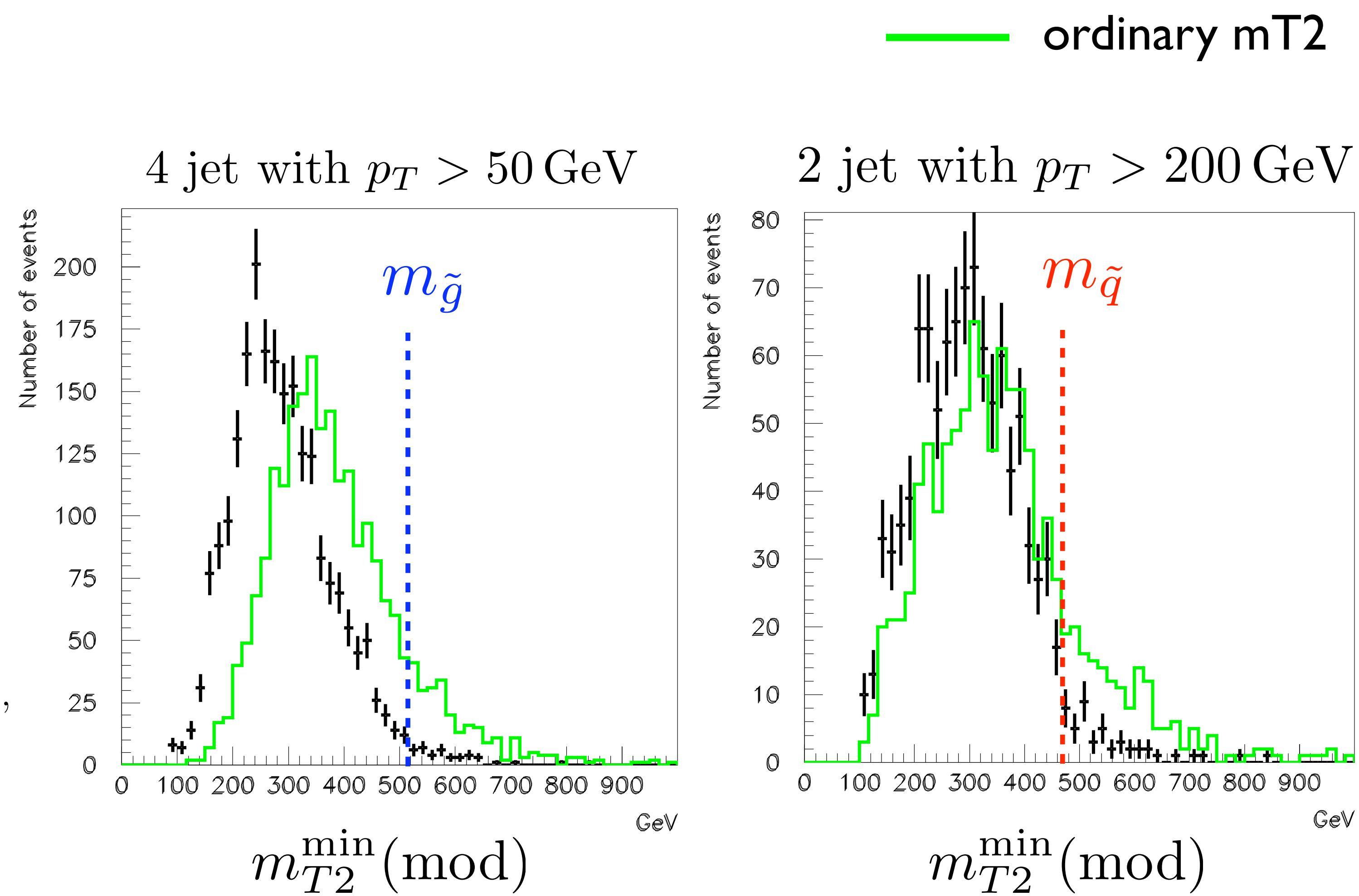
$m_{squark}$ :

$m_{T2}^{\min}(\mathrm{mod})\Big|^{2\,\mathrm{jets\ with}}_{p_T>200\mathrm{GeV}}$

$E_T^{\mathrm{miss}} > \max(100\,\mathrm{GeV}, 0.2M_{\mathrm{eff}})$,

$M_{\mathrm{eff}} > 500\,\mathrm{GeV}$,

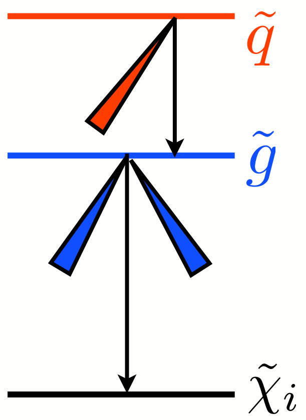
$N^{\mathrm{jets(parton)}}_{p_T>100\,\mathrm{GeV}} \geq 1$,



# $E_{CM}$ = 7 TeV, L = 1 fb$^{-1}$

M.M.Nojiri, K.S. '10

msq > mgl




| | $m_0$ | $m_{1/2}$ | $m_{gluino}$ | $m_{squark}$(uL) |
|---|---|---|---|---|
| Point 5' | 700 | 210 | 558 | 825 |

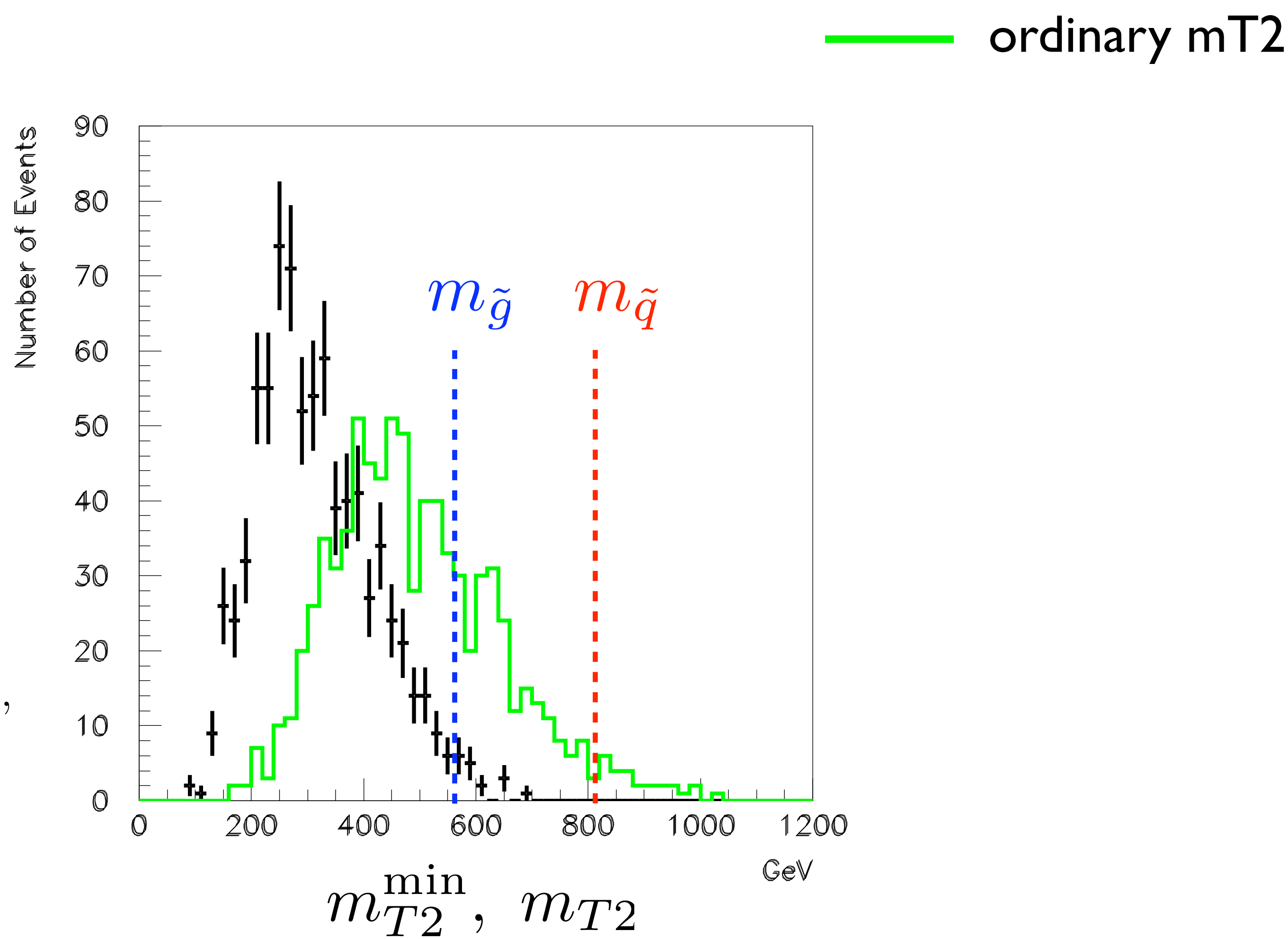
$m_{gluino}$ : $m_{T2}^{min}$

$m_{squark}$ : $m_{T2}$

$E_T^{miss} > \max(100\,\mathrm{GeV}, 0.2 M_{\rm eff})$,

$M_{\rm eff} > 500\,\mathrm{GeV}$,

$N^{\rm jets(parton)}_{p_T > 100\,\mathrm{GeV}} \geq 1$,



# Summary

• Existence of two missing particles and large combinatorial background make measurements of new particle masses difficult.

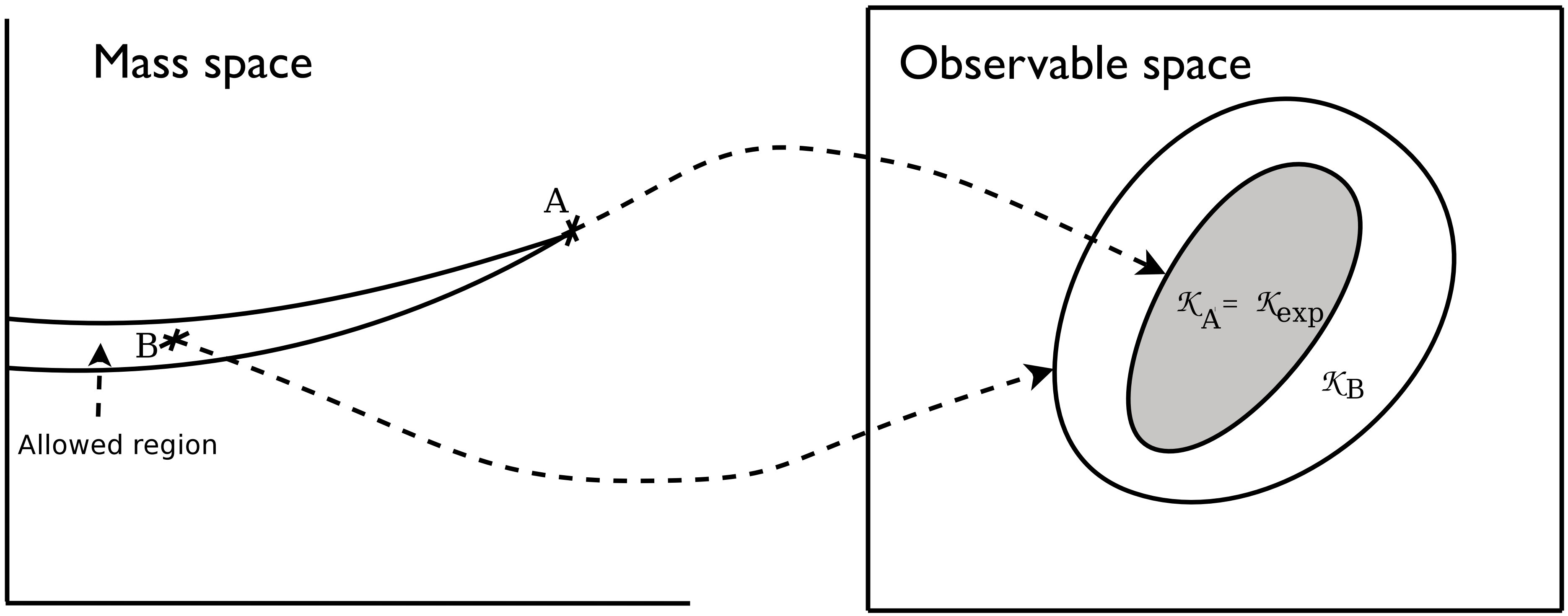
• Various methods have been proposed to overcome this issue.

• In the early stage of the LHC, inclusive analysis will be important.

• By using $m_{T2}^{min}$ and $m_{T2}^{min}$(mod), we can overcome ISR contamination to gluino and squark mass measurements.

# Kinematical Constraints

H-C.Cheng, et.al, 0707.0030



| | Point A | Point B | Point C |
|---|---|---|---|
| Events (S/B) | 326 (4.2) | 499 (4.5) | 292 (2.8) |
| Sharing (S/B) | 219 (8.1) | 341 (9.7) | 172 (4.9) |
| $M_1$ (True ; Best) | 231890 ; 222500 | 286157 ; 282500 | 316274 ; 317500 |
| $M_2$ (True ; Best) | 5624 ; 5000 | 14520 ; 14200 | 6815 ; 6600 |
| $M_3$ (True ; Best) | 12872 ; 11700 | 10293 ; 9900 | 19812 ; 18900 |

Signal / background ratios are enhanced at the best fit cell.

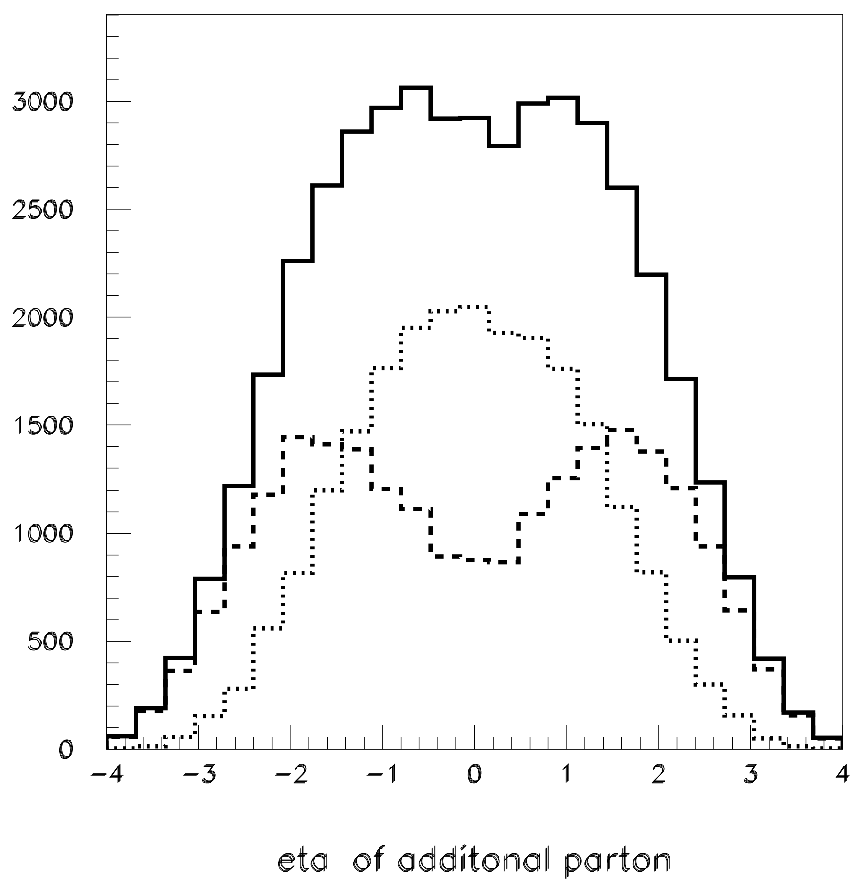
# Statistical approach

- $\Delta\chi^2$ is obtained from the log likelihood function as follows:

$$\ln L(\mathbf{M}) = \sum_{i_{\rm ev}}^{N} \ln f_{i_{\rm ev}}(\mathbf{M}) \qquad \Delta\chi^2(\mathbf{M}) = 2(\ln L(\mathbf{M})_{\rm max} - \ln L(\mathbf{M})),$$

The relationship between $\Delta\chi^2$ and CL, when $\Delta\chi^2$ has 3 arguments →

| CL (%) | $\Delta\chi^2$ |
|---|---|
| 68.27 | 3.53 |
| 90. | 6.25 |
| 95. | 7.82 |
| 95.45 | 8.03 |
| 99. | 11.34 |
| 99.73 | 14.16 |


3000
2500
2000
1500
1000
500
0
−4
−3
−2
−1
0
1
2
3
4
eta of additonal parton