Simulation of Old and New Physics

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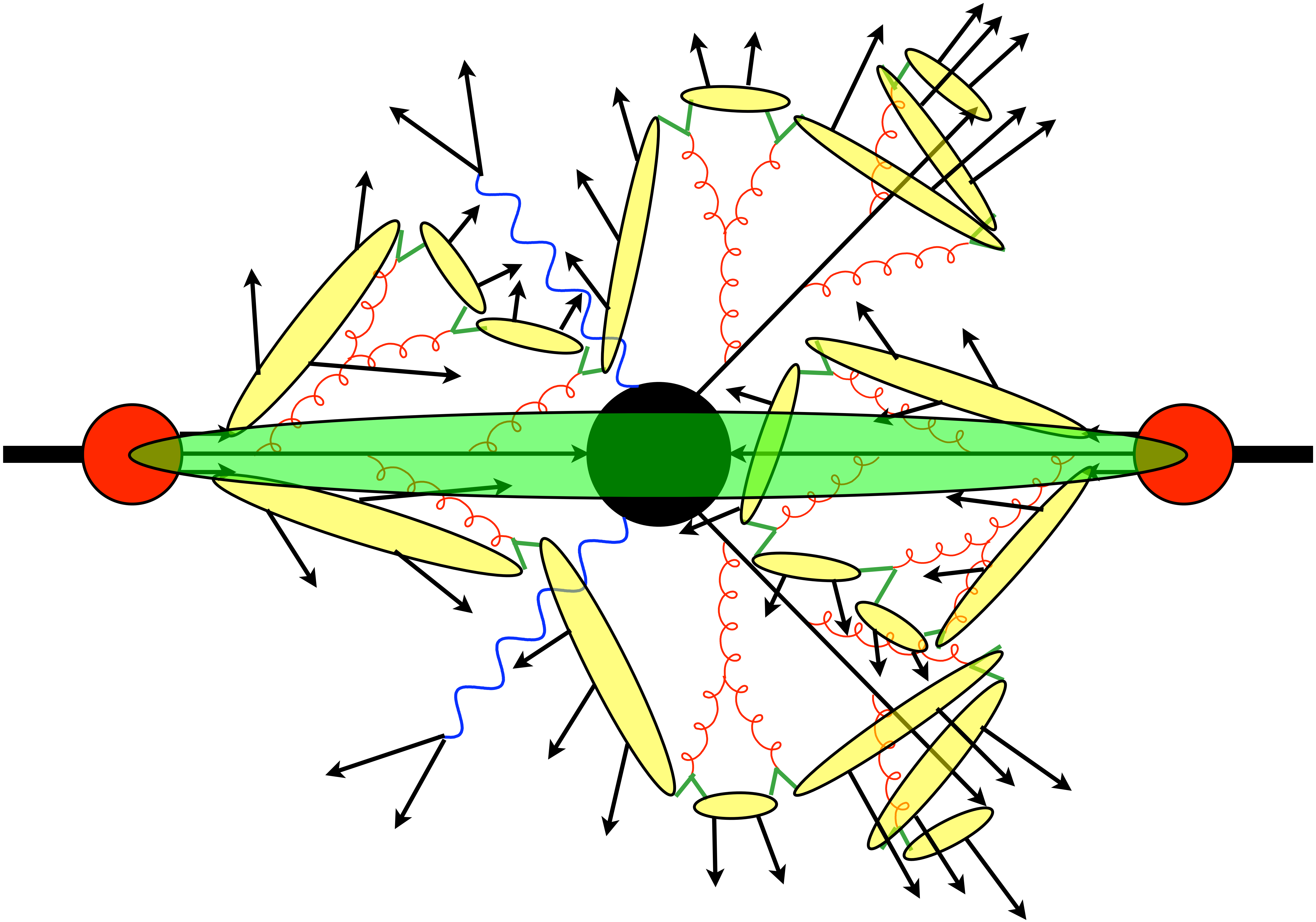
'LHC Era' Workshop, Paris, 13-17 Nov 2006

- Event generators
- Old physics: multijets
- Old Physics: matching to NLO
- New physics: SUSY vs UED
- New physics: black holes

LHC Event Simulation



General-Purpose Event Generators

- PYTHIA
  - Virtuality/k_T-ordered shower, string hadronization
  - v6 Fortran; v8 C++
- HERWIG
  - Angular-ordered shower, cluster hadronization
  - v6 Fortran; Herwig++
- SHERPA
  - Virtuality-ordered shower, string/cluster hadronization
  - C++

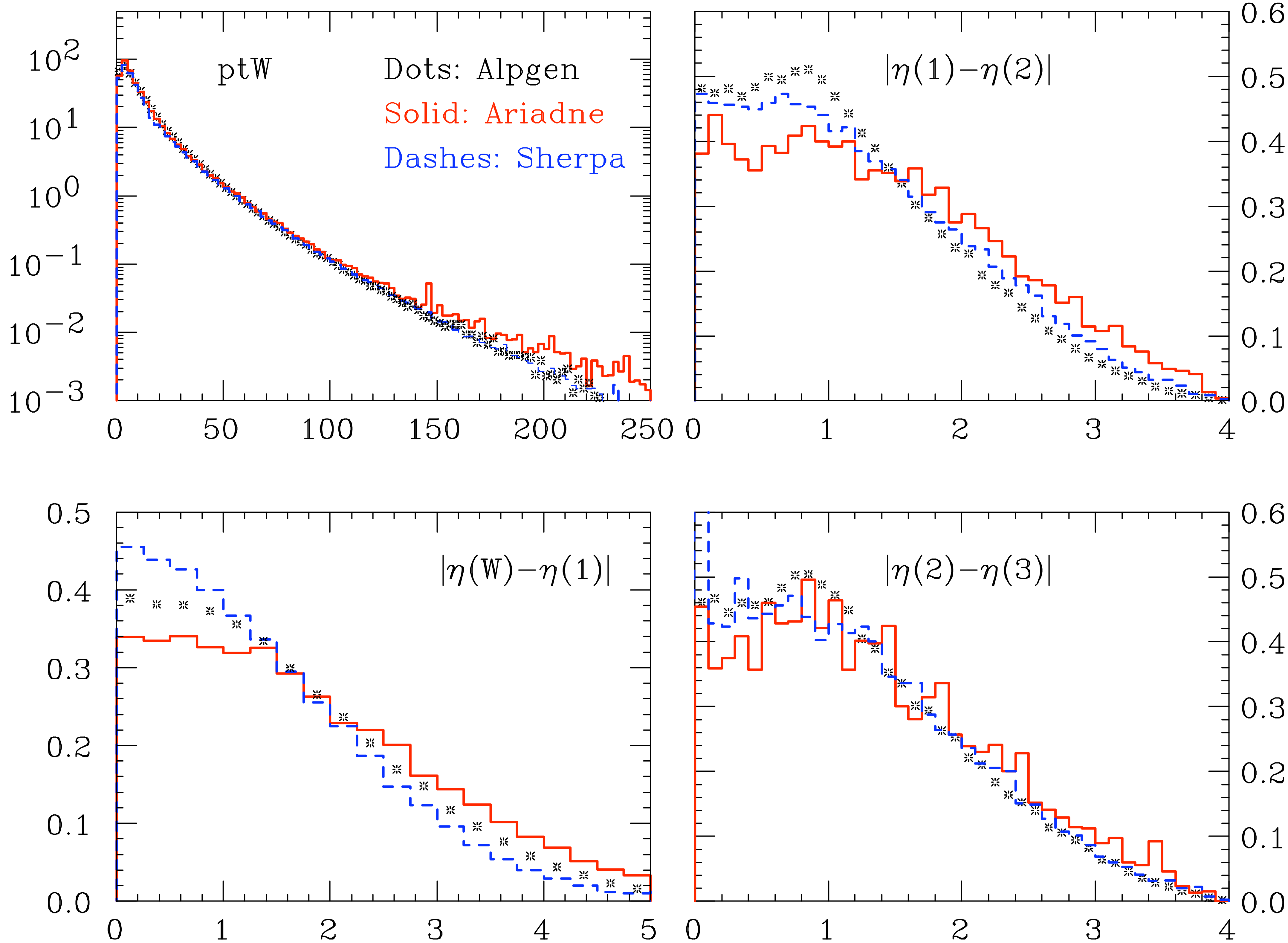
HERWIG Event Generator

- Most important SM & MSSM processes at LO
  - ➔ spin correlations included
  - ➔ parton showers at leading log (LL)
  - ➔ interface to JIMMY underlying event (J Butterworth et al.)
  - ➔ no showering from SUSY particles
  - ➔ G Corcella et al., hep-ph/0210213 & refs therein
- MC@NLO provides some SM processes at NLO
  - ➔ S Frixione & BW, hep-ph/0506182 & refs therein
- Interface to CHARYBDIS black hole generator
  - ➔ C Harris, P Richardson & BW, hep-ph/0307305

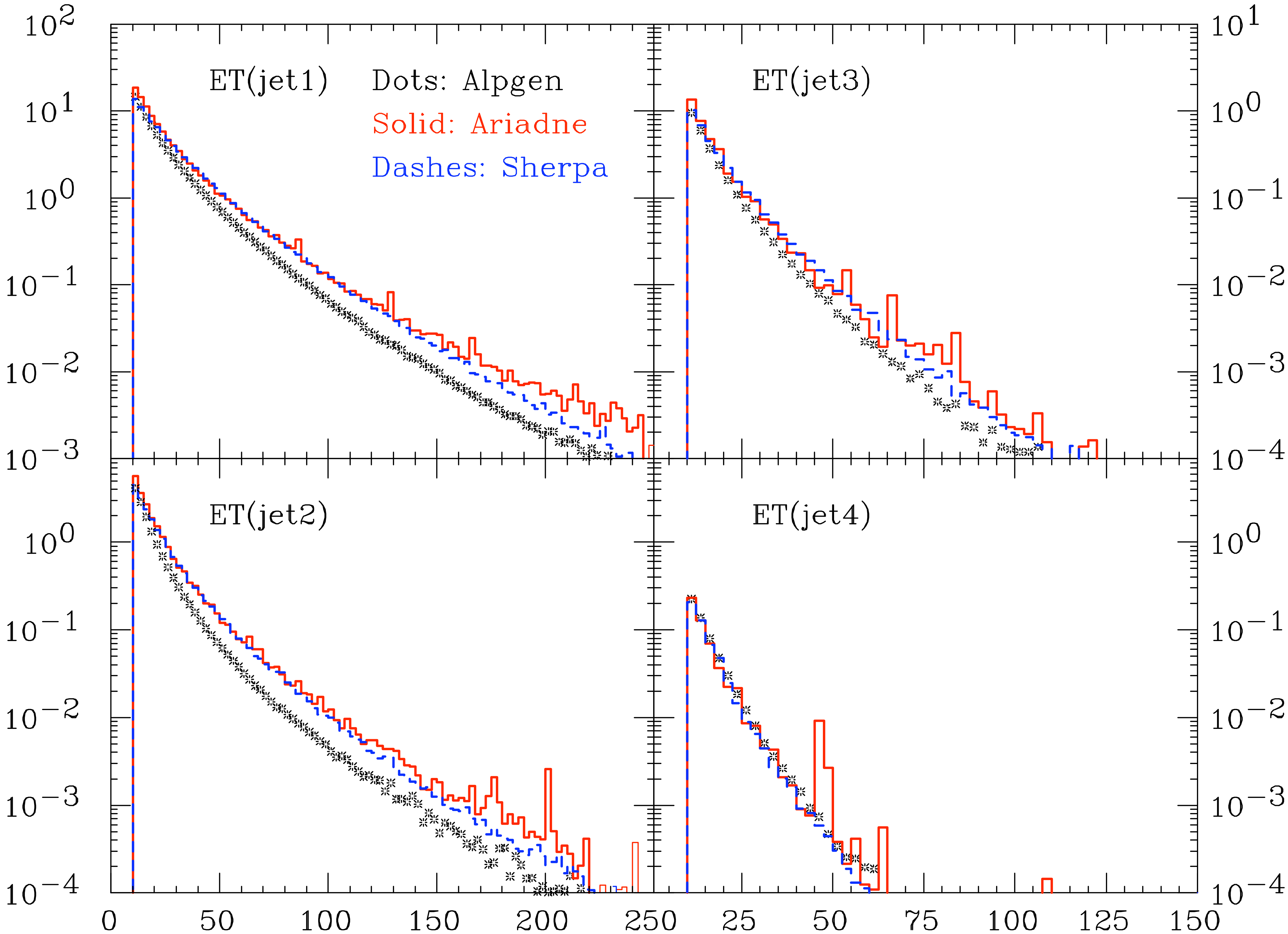
Multijets

- Important backgrounds to new physics
- Only LO available up to high parton multiplicity (ALPGEN, AMEGIC++, MADGRAPH, HELAC,...)
  - ➜ OK for hard, well-separated jets
  - ➜ Strong sensitivity to α_s scale
  - ➜ No jet structure, interjet flow, underlying event
- Combine LO matrix elements + parton showers
  - ➜ Define jet resolution scale
  - ➜ Cancel leading scale dependence
  - ➜ CKKW, Ariadne and MLM schemes
  - ➜ See S Höche el al., hep-ph/0602031

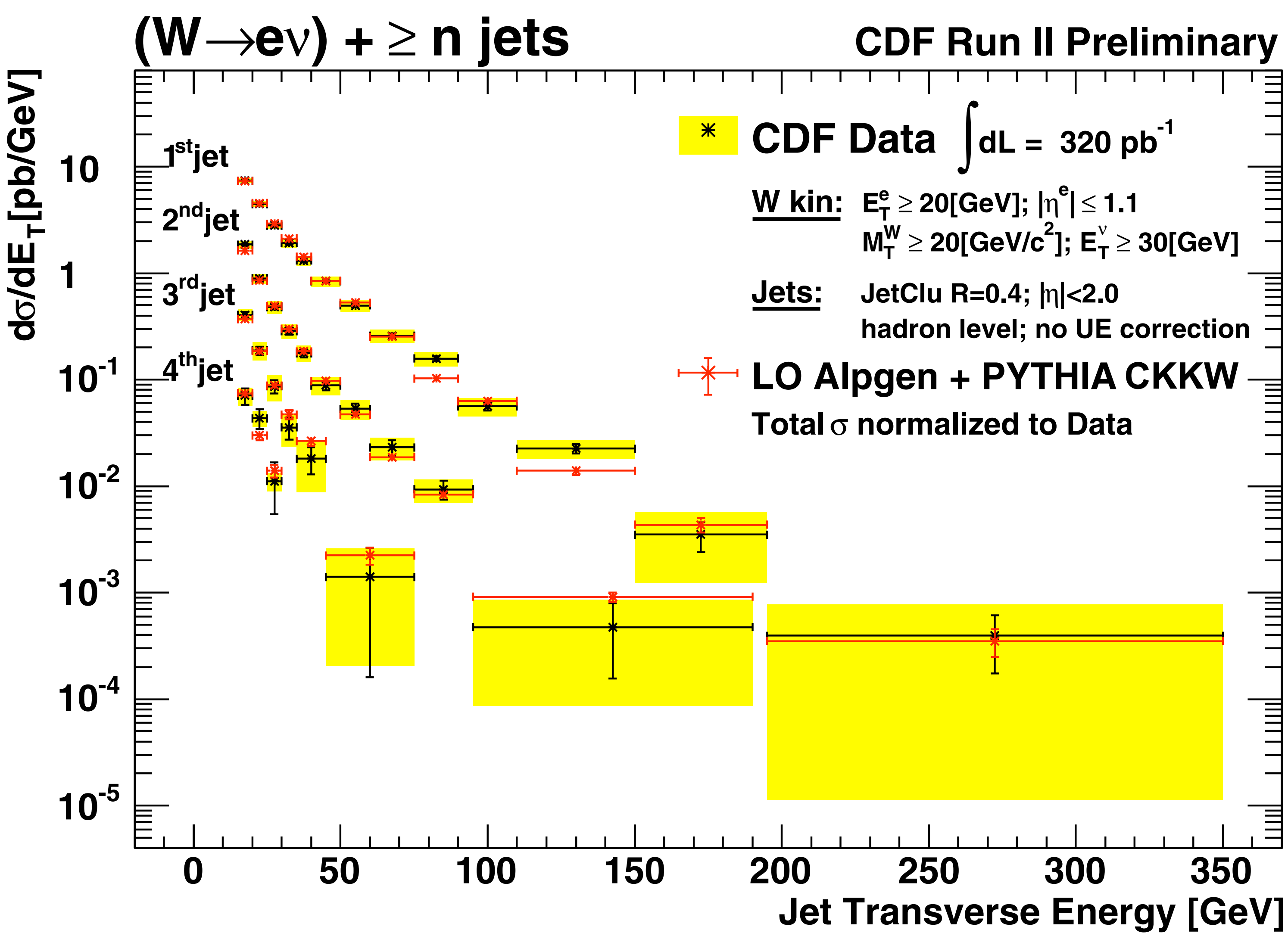
W + Multijets (Tevatron)

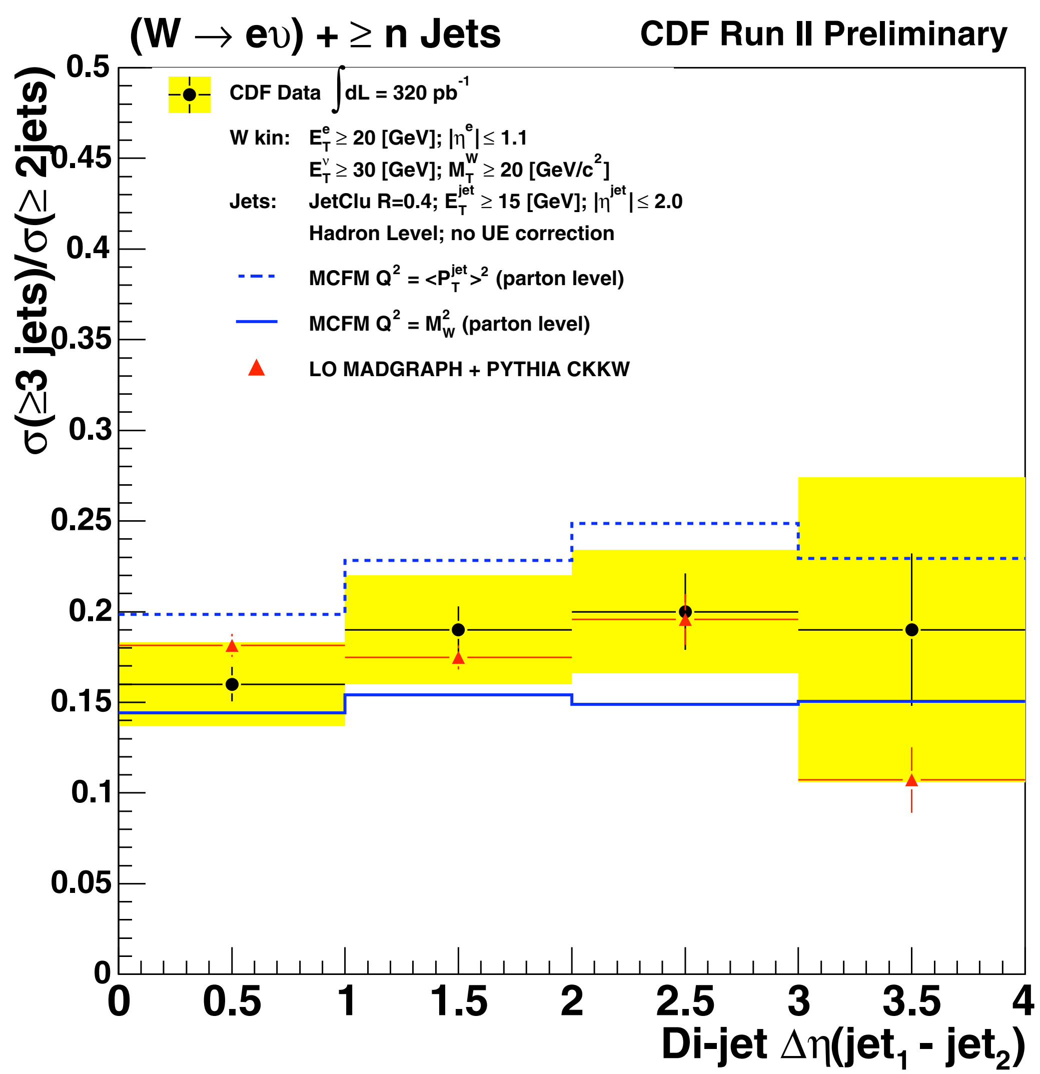


W + Multijets (Tevatron)



Comparisons with Tevatron data

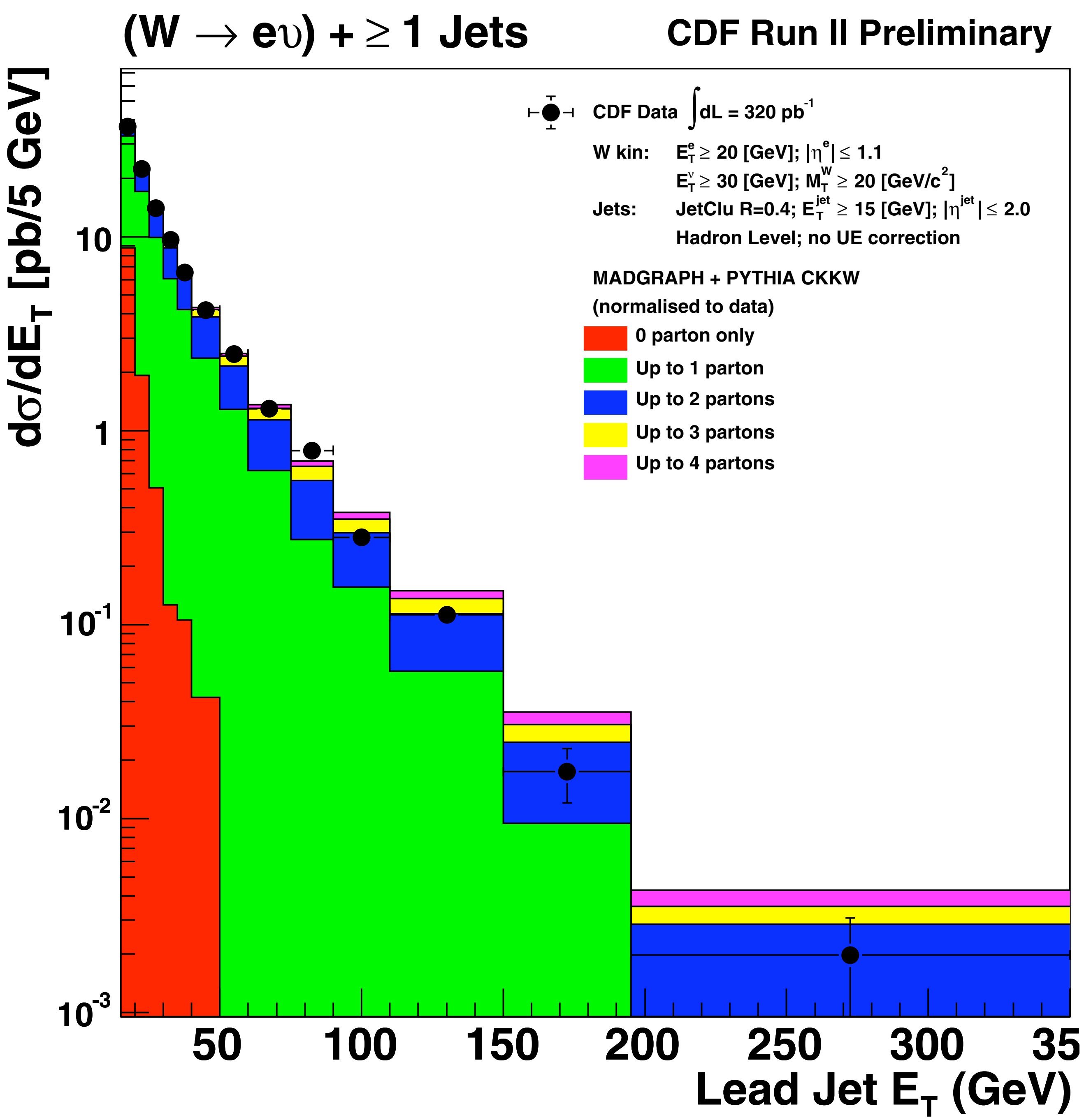


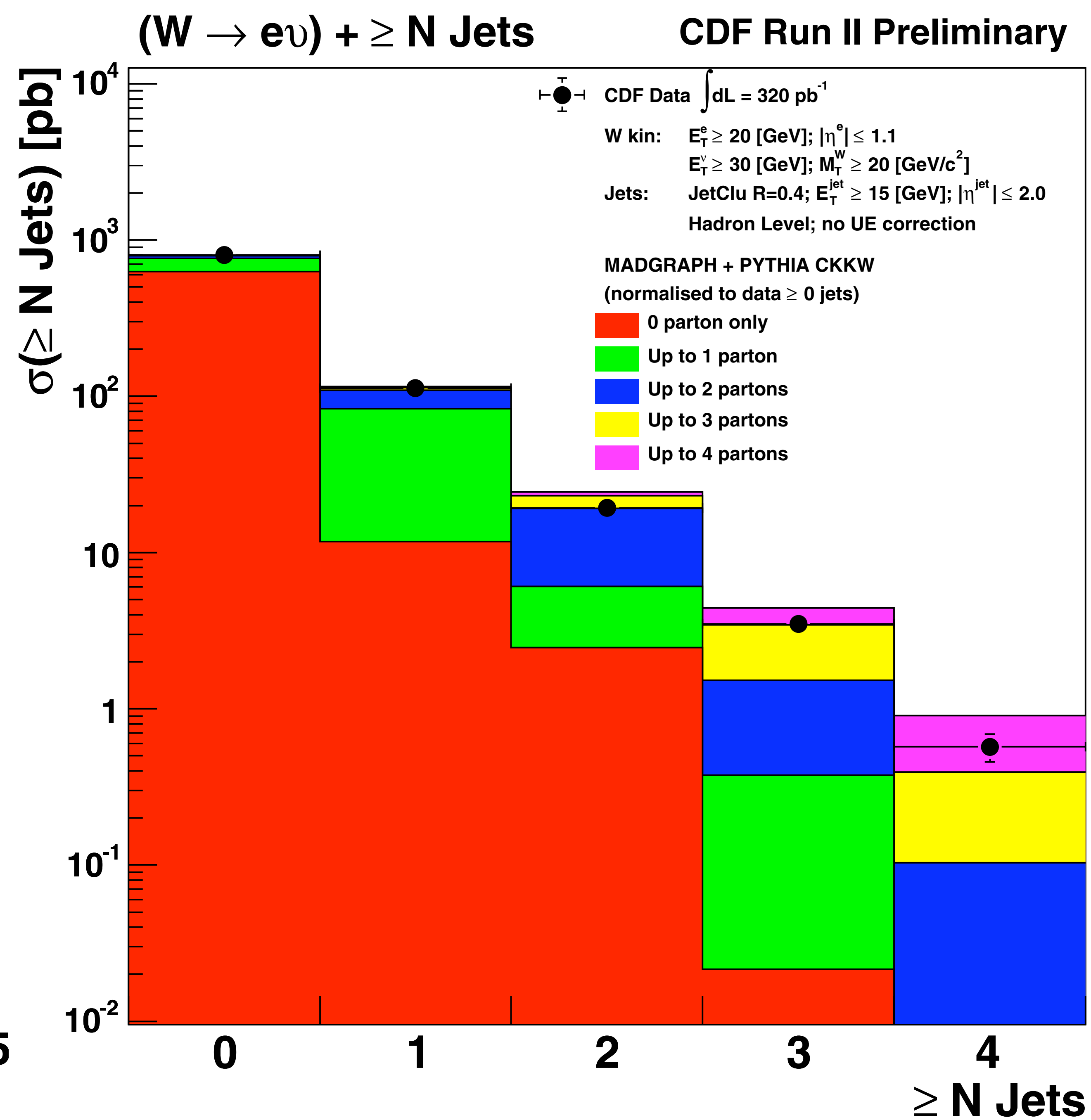


from JM Campbell, JW Huston & WJ Stirling, hep-ph/0611148

➡ M.E. + PYTHIA CKKW looks good

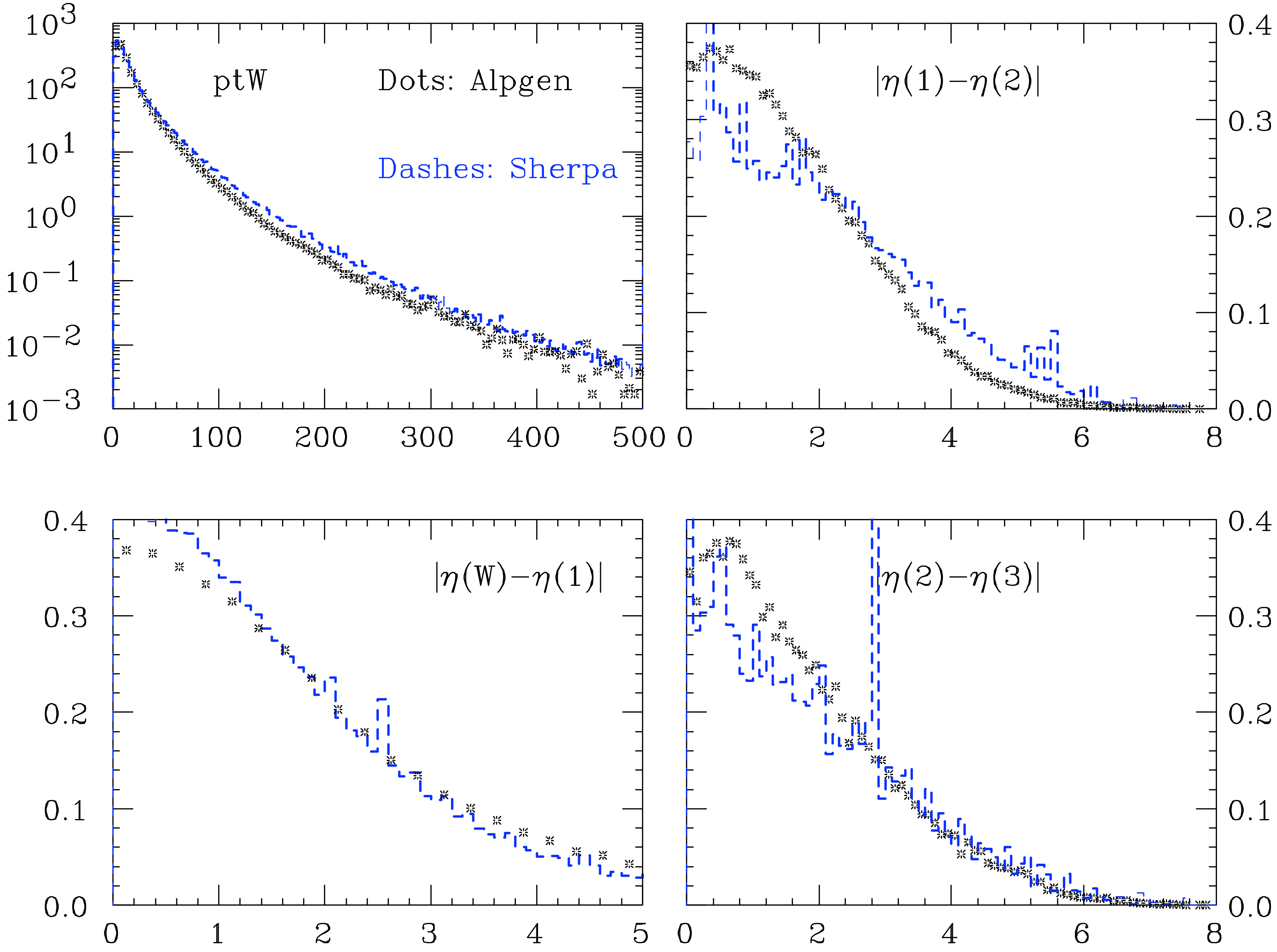
Comparisons with Tevatron data (2)



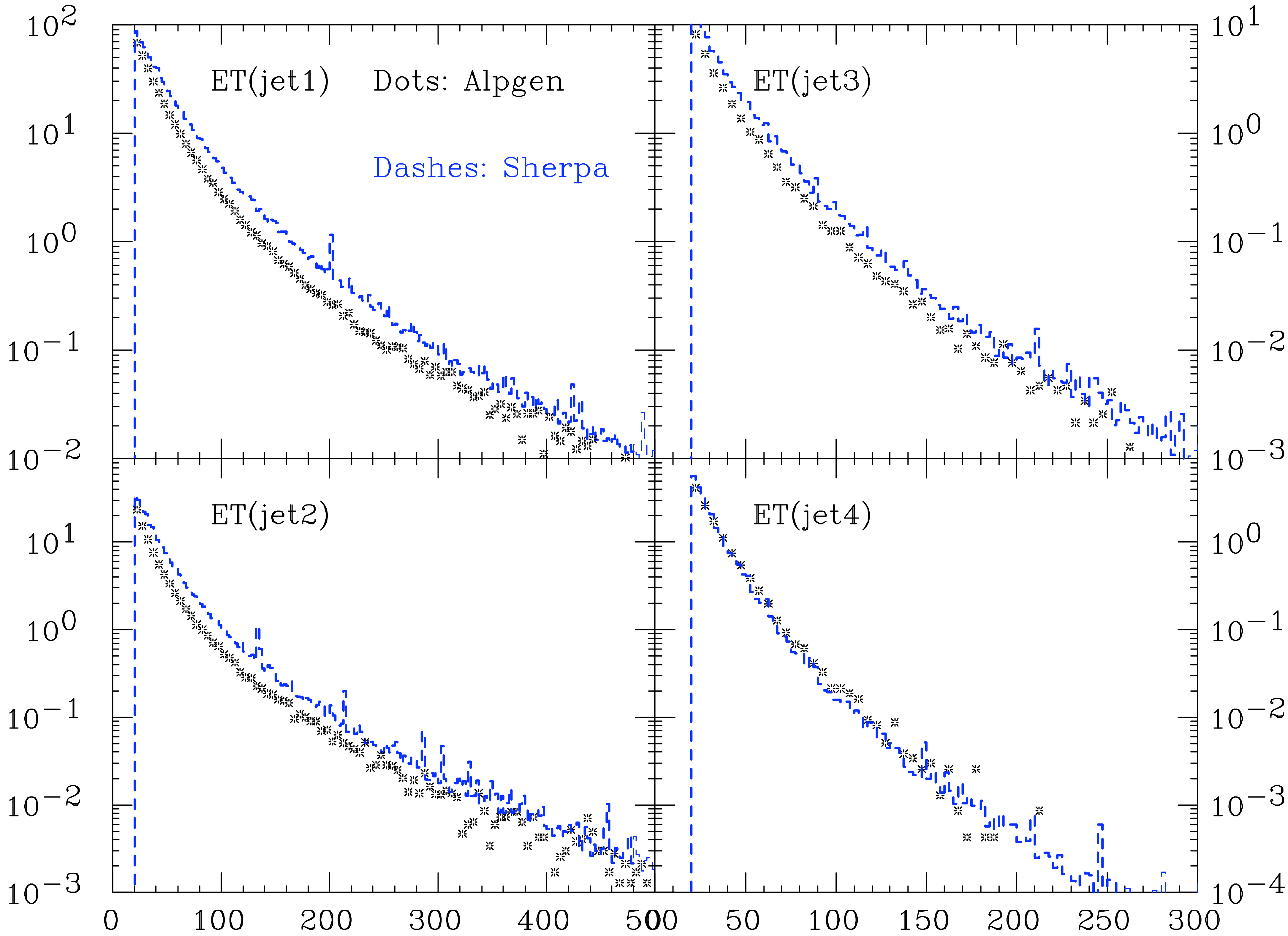


➡ Several parton multiplicities contribute to jets

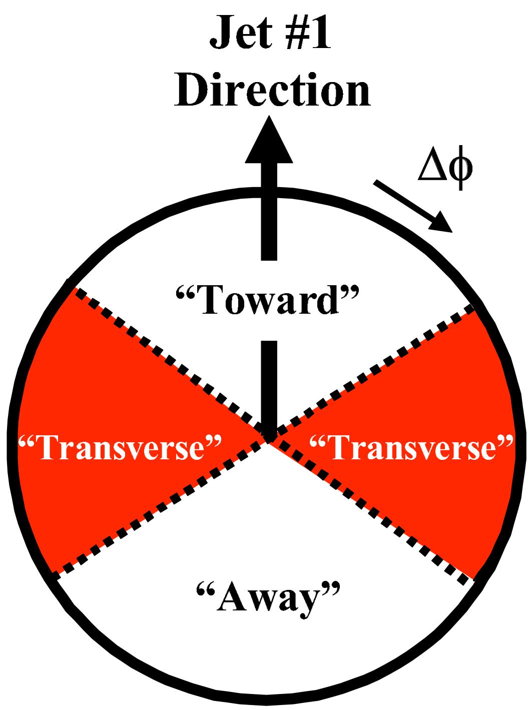
W + Multijets (LHC)

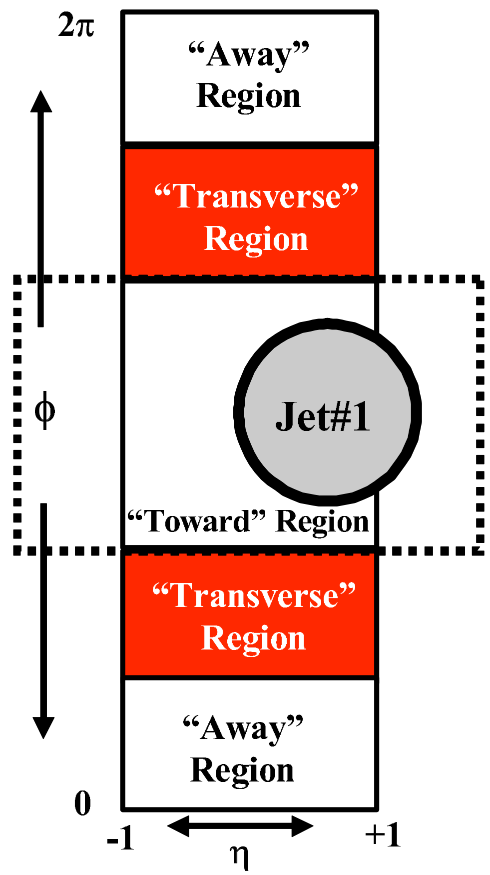


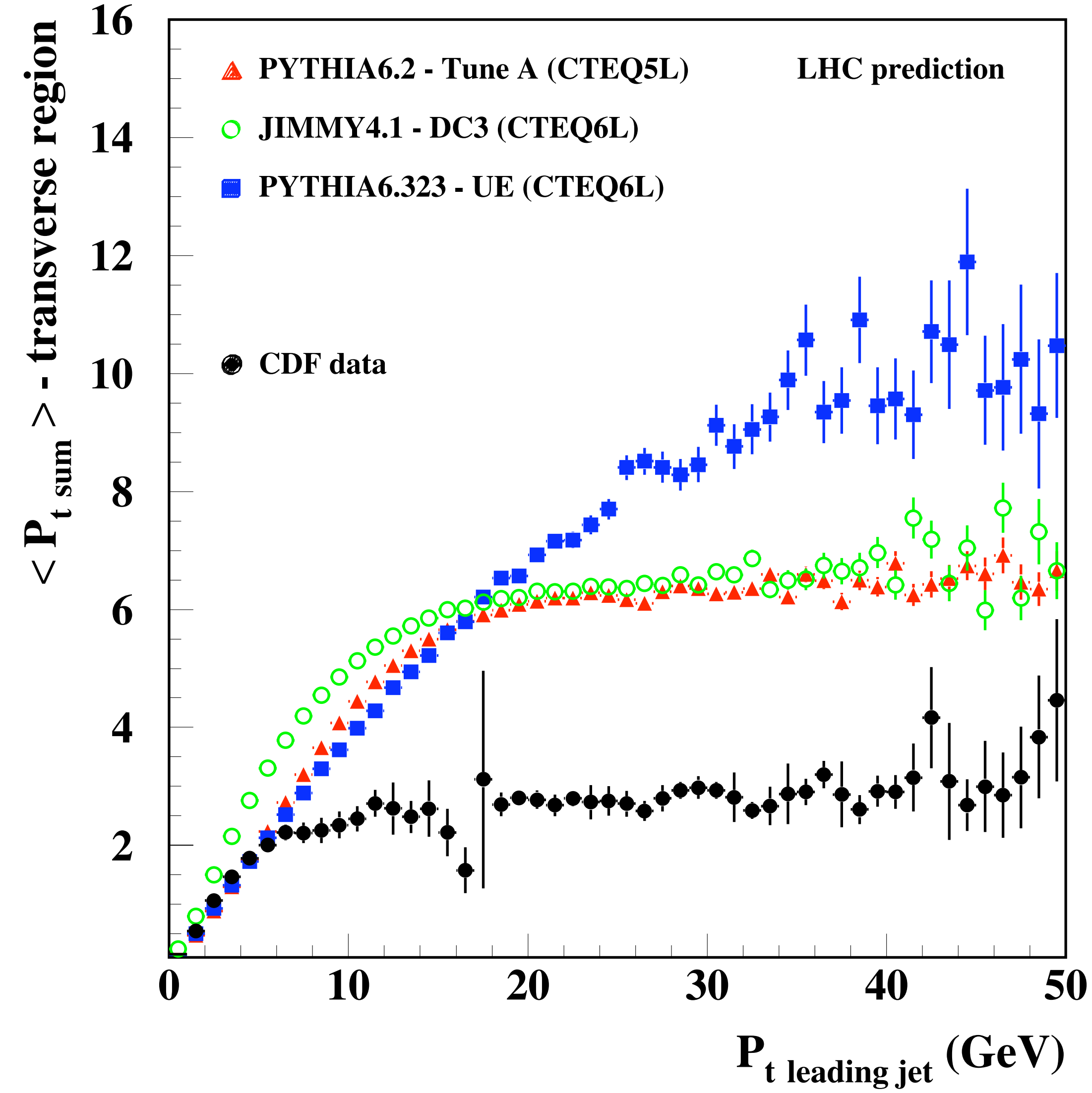
W + Multijets (LHC)



Underlying Event







Multiple parton interactions

➡ Rise in activity between jets

➡ Extrapolation from Tevatron still uncertain

Matching to NLO

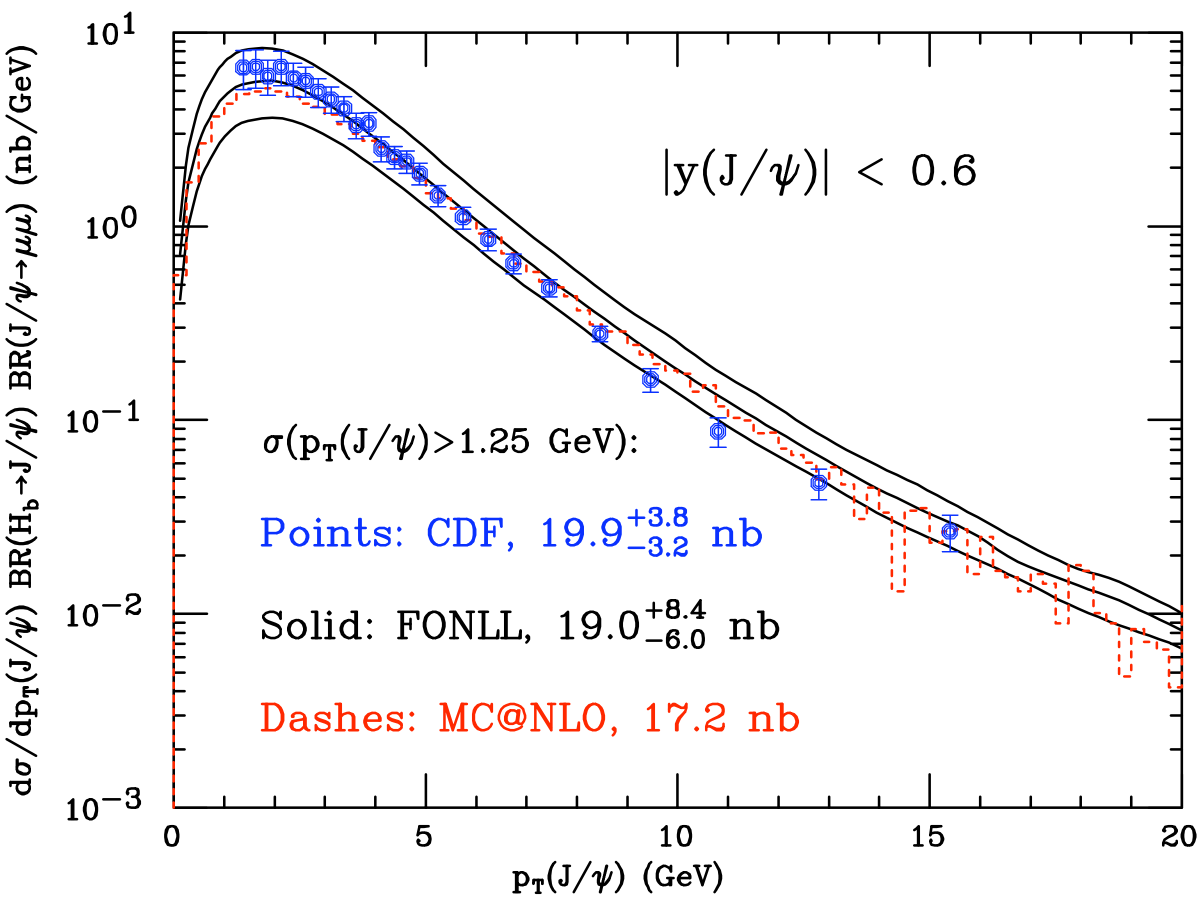
- Must avoid double-counting at NLO
  - ➔ Modify NLO and/or parton shower (PS)
- MC@NLO: don't touch shower
  - ➔ Subtract NLO PS terms from exact NLO
  - ➔ Stabilizes NLO but some weights < 0
- Nason; Nagy-Soper: modify shower
  - ➔ Can avoid negative weights
  - ➔ Difficult to implement coherence

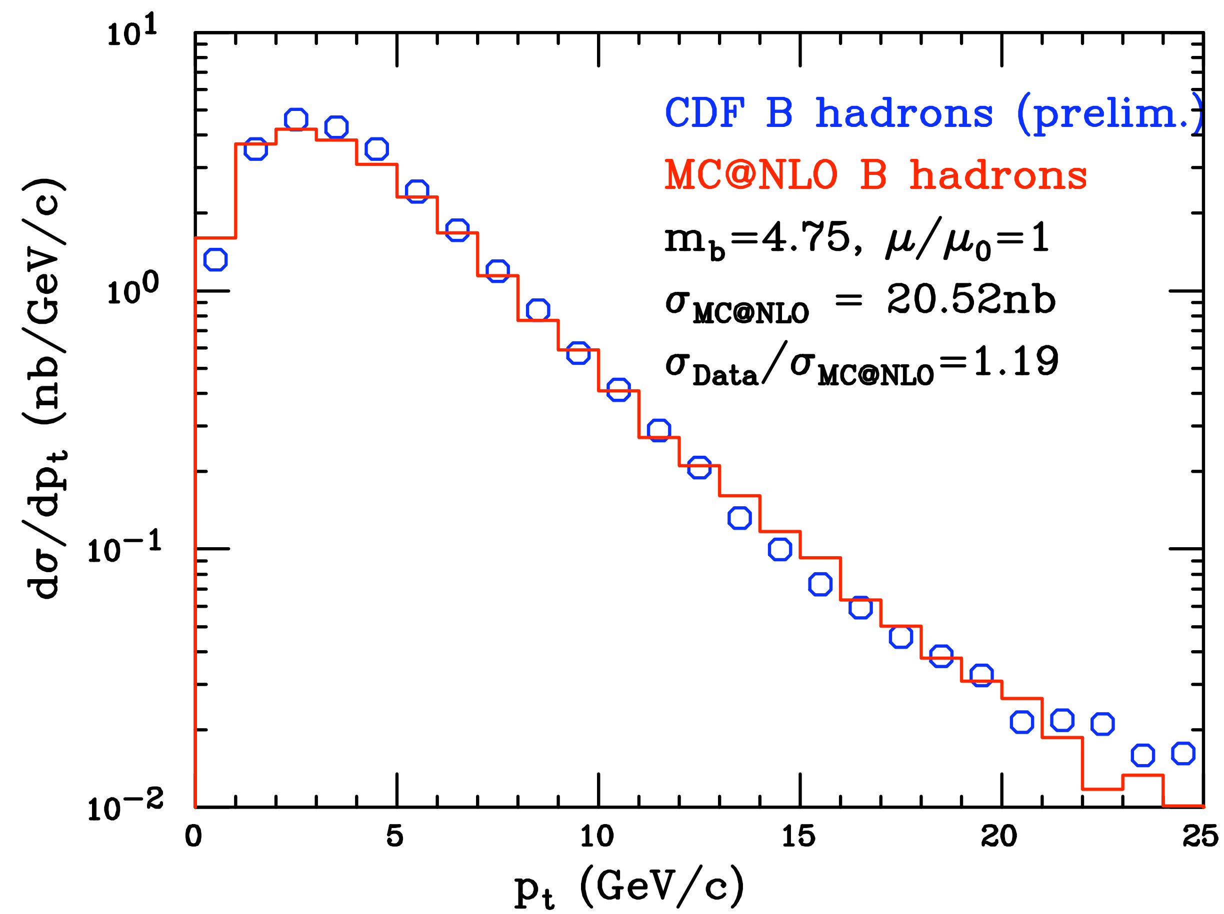
MC@NLO Processes

IPROC	IV	IL_1	IL_2	Spin	Process
–1350–IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1360–IL				✓	$H_1H_2 \to (Z \to) l_{IL}\bar{l}_{IL} + X$
–1370–IL				✓	$H_1H_2 \to (\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1460–IL				✓	$H_1H_2 \to (W^+ \to) l^+_{IL}\nu_{IL} + X$
–1470–IL				✓	$H_1H_2 \to (W^- \to) l^-_{IL}\bar{\nu}_{IL} + X$
–1396				×	$H_1H_2 \to \gamma^*(\to \sum_i f_i\bar{f}_i) + X$
–1397				×	$H_1H_2 \to Z^0 + X$
–1497				×	$H_1H_2 \to W^+ + X$
–1498				×	$H_1H_2 \to W^- + X$
–1600–ID					$H_1H_2 \to H^0 + X$
–1705					$H_1H_2 \to b\bar{b} + X$
–1706				×	$H_1H_2 \to t\bar{t} + X$
–2000–IC				×	$H_1H_2 \to t/\bar{t} + X$
–2001–IC				×	$H_1H_2 \to \bar{t} + X$
–2004–IC				×	$H_1H_2 \to t + X$
–2600–ID	1	7		×	$H_1H_2 \to H^0W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0(W^+ \to) l^+_i\nu_i + X$
–2600–ID	-1	7		×	$H_1H_2 \to H^0W^- + X$
–2600–ID	-1	i		✓	$H_1H_2 \to H^0(W^- \to) l^-_i\bar{\nu}_i + X$
–2700–ID	0	7		×	$H_1H_2 \to H^0Z + X$
–2700–ID	0	i		✓	$H_1H_2 \to H^0(Z \to) l_i\bar{l}_i + X$
–2850		7	7	×	$H_1H_2 \to W^+W^- + X$
–2850		i	j	✓	$H_1H_2 \to (W^+ \to) l^+_i\nu_i(W^- \to) l^-_j\bar{\nu}_j + X$
–2860		7	7	×	$H_1H_2 \to Z^0Z^0 + X$
–2870		7	7	×	$H_1H_2 \to W^+Z^0 + X$
–2880		7	7	×	$H_1H_2 \to W^-Z^0 + X$

MC@NLO: B production at Tevatron

- $B \to J/\psi$ results from Tevatron Run II $\Rightarrow$ B hadrons

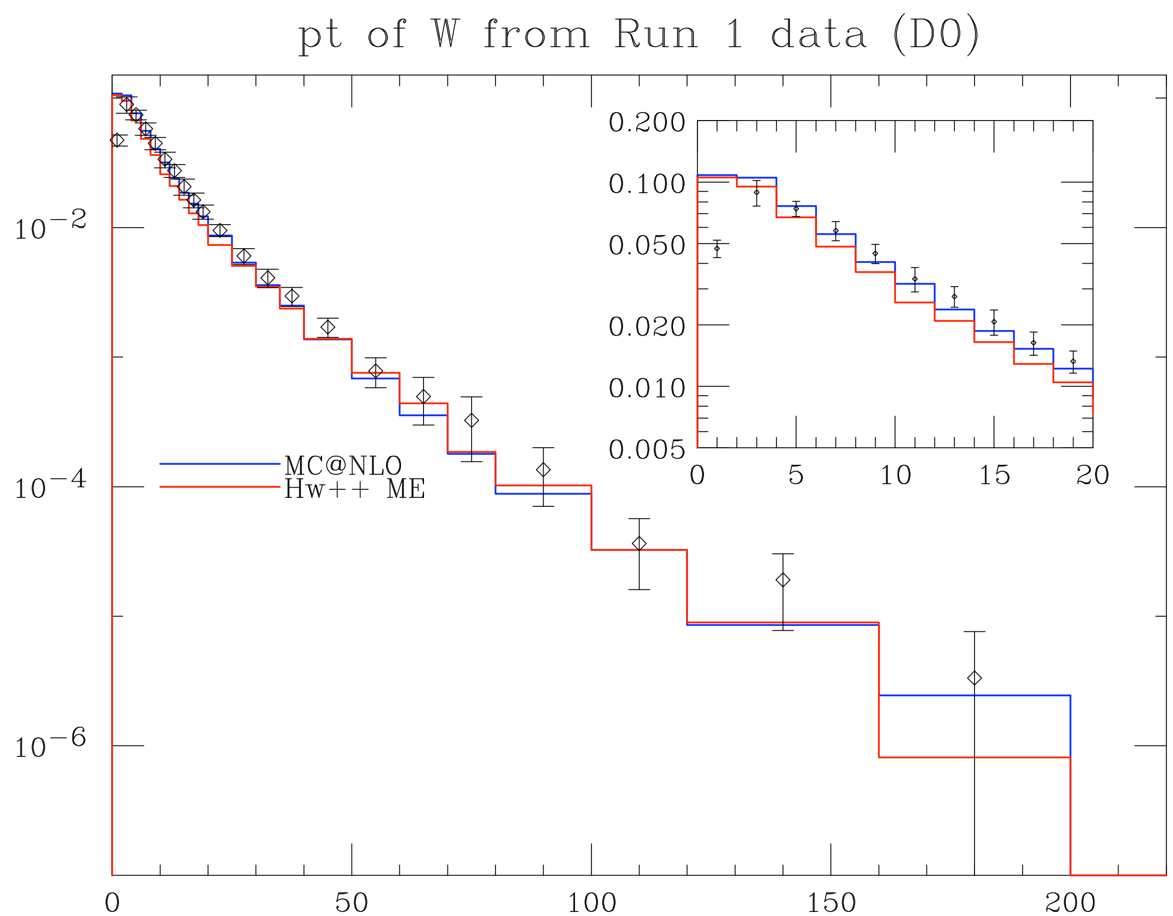


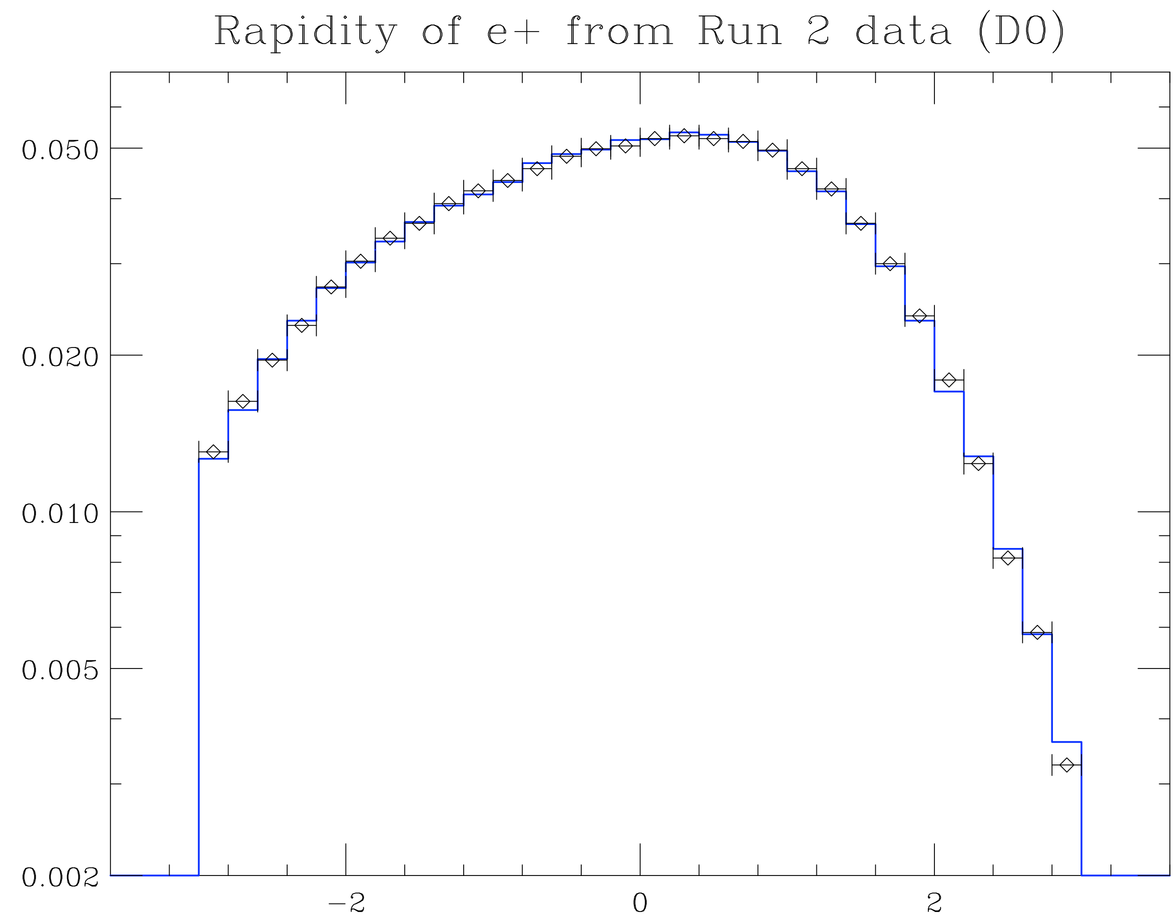


S Frixione, P Nason & BW, hep-ph/0305252

➡ No longer any significant discrepancy

MC@NLO: W production at Tevatron



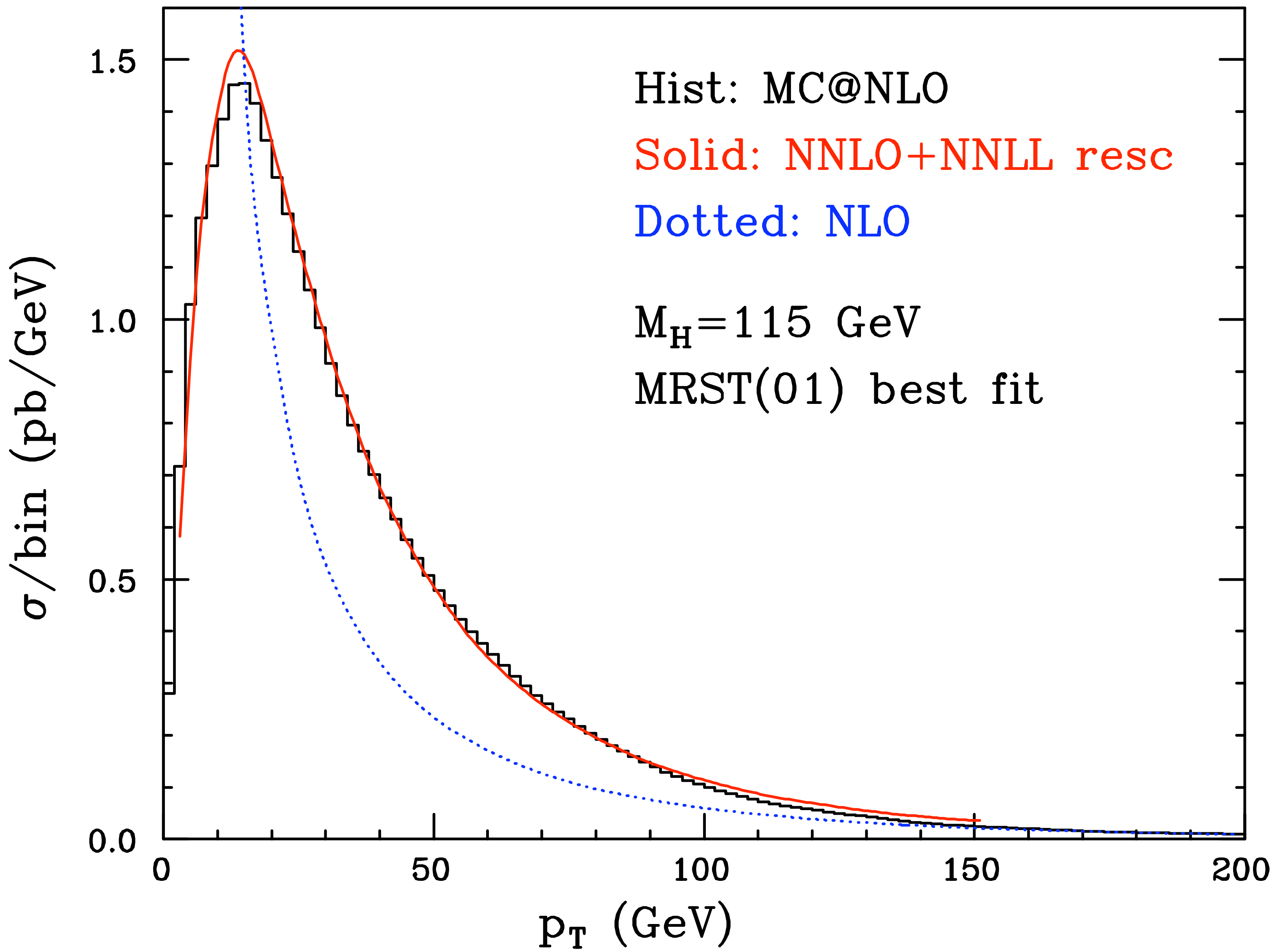


O Latunde-Dada, in prep.

- First results from MC@NLO with Herwig++

(intrinsic p_T still missing)

MC@NLO: Higgs Production at LHC



V Del Duca, S Frixione, C Oleari & BW, in prep.

➡ Good agreement with state-of-the-art resummation

New Physics at LHC

- SUSY vs UED [*]
- Black Holes [+]

[*] JM Smillie & BW, hep-ph/0507170

[+] CM Harris et al., hep-ph/041022

Spin Correlations in SUSY & UED

- SUSY: new particles are superpartners

  $q \leftrightarrow \widetilde{q}\ ,\ \ g \leftrightarrow \widetilde{g}\ ,\ \ l \leftrightarrow \tilde{l}\ ,\ \ (\gamma, Z, \ldots) \leftrightarrow (\widetilde{\chi}^0_1, \widetilde{\chi}^0_2, \ldots)$

  ➜ spins differ by one-half

- UED: new particles are KK excitations

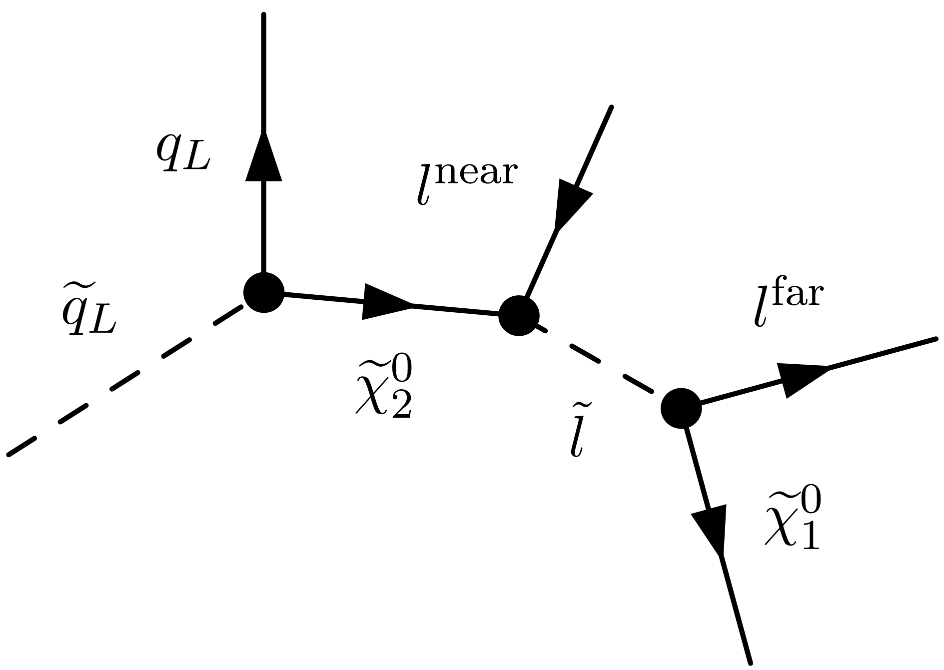
  $q \leftrightarrow q^*\ ,\ \ g \leftrightarrow g^*\ ,\ \ l \leftrightarrow l^*\ ,\ \ (\gamma, Z, \ldots) \leftrightarrow (\gamma^*, Z^*, \ldots)$

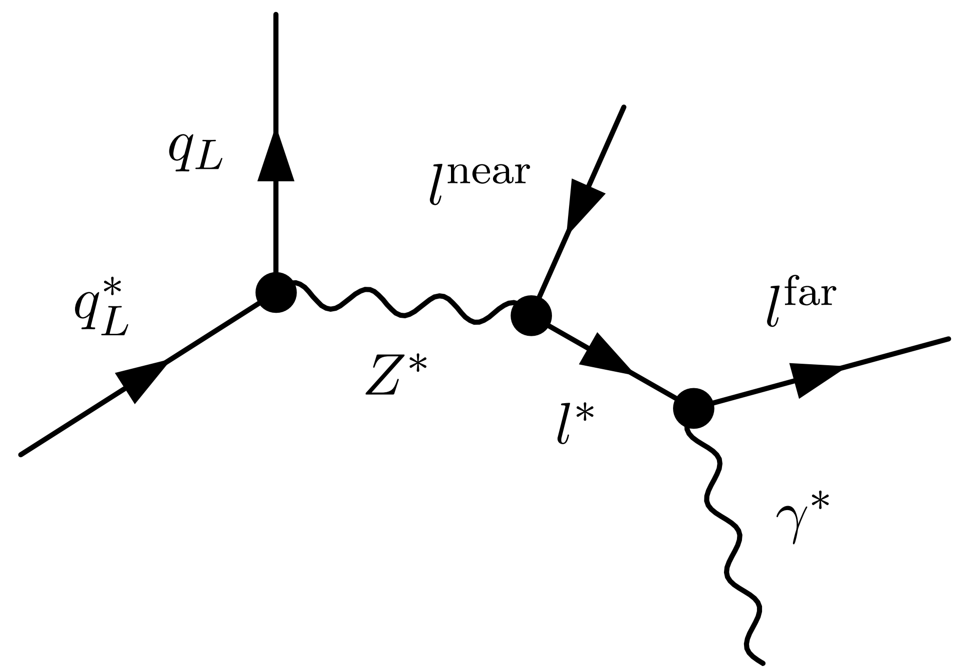
  ➜ spins are the same!

- Suppose masses have been measured: how could we distinguish?

  ➜ need evidence on spins to be sure

SUSY and UED decay chains





➡ Two distinct helicity structures, with different spin correlations:

- Process 1: $\{q, l^{\rm near}, l^{\rm far}\} = \{q_L, l_L^-, l_L^+\}$ or $\{\bar{q}_L, l_L^+, l_L^-\}$ or $\{q_L, l_R^+, l_R^-\}$ or $\{\bar{q}_L, l_R^-, l_R^+\}$;
- Process 2: $\{q, l^{\rm near}, l^{\rm far}\} = \{q_L, l_L^+, l_L^-\}$ or $\{\bar{q}_L, l_L^-, l_L^+\}$ or $\{q_L, l_R^-, l_R^+\}$ or $\{\bar{q}_L, l_R^+, l_R^-\}$.

UED and SUSY mass spectra

- UED models tend to have quasi-degenerate spectra

γ^*	Z^*	q_L^*	l_R^*	l_L^*
501	536	598	505	515

Table 1: UED masses in GeV, for $R^{-1} = 500\text{GeV}$, $\Lambda R = 20$, $m_h = 120\text{GeV}$, $\overline{m}_h^2 = 0$ and vanishing boundary terms at cut-off scale Λ.

($M_n \sim n/R$ broken by boundary terms and loops, with low cutoff)

- SUSY spectra typically more hierarchical

$\widetilde{\chi}_1^0$	$\widetilde{\chi}_2^0$	$\widetilde{u}_L$	$\widetilde{e}_R$	$\widetilde{e}_L$
96	177	537	143	202

Table 2: SUSY masses in GeV, for SPS point 1a.

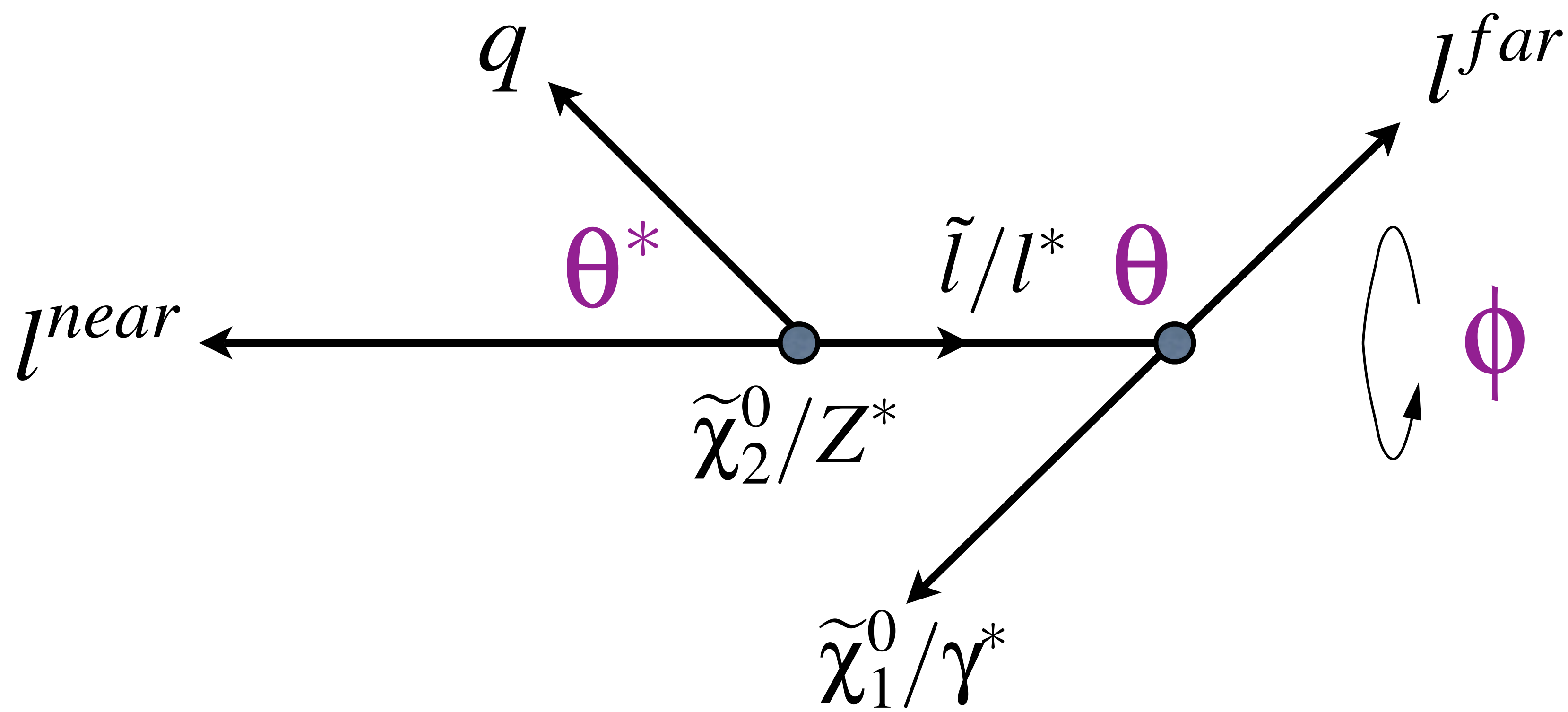
(high-scale universality)

Production cross sections (pb)

Masses	Model	σ_{all}	σ_{q^*}	$\sigma_{\bar{q}^*}$	f_q
UED	UED	253	163	84	0.66
UED	SUSY	28	18	9	0.65
SPS 1a	UED	433	224	80	0.74
SPS 1a	SUSY	55	26	11	0.70

- $\sigma_{\text{UED}} \gg \sigma_{\text{SUSY}}$ for same masses (100 pb = 1/sec)
  - $q^*/\bar{q}^* \sim 2 \Rightarrow$ charge asymmetry

Angular variables



θ^* defined in $\tilde{\chi}_2^0/Z^*$ rest frame

θ, ϕ defined in $\tilde{l}/l^*$ rest frame

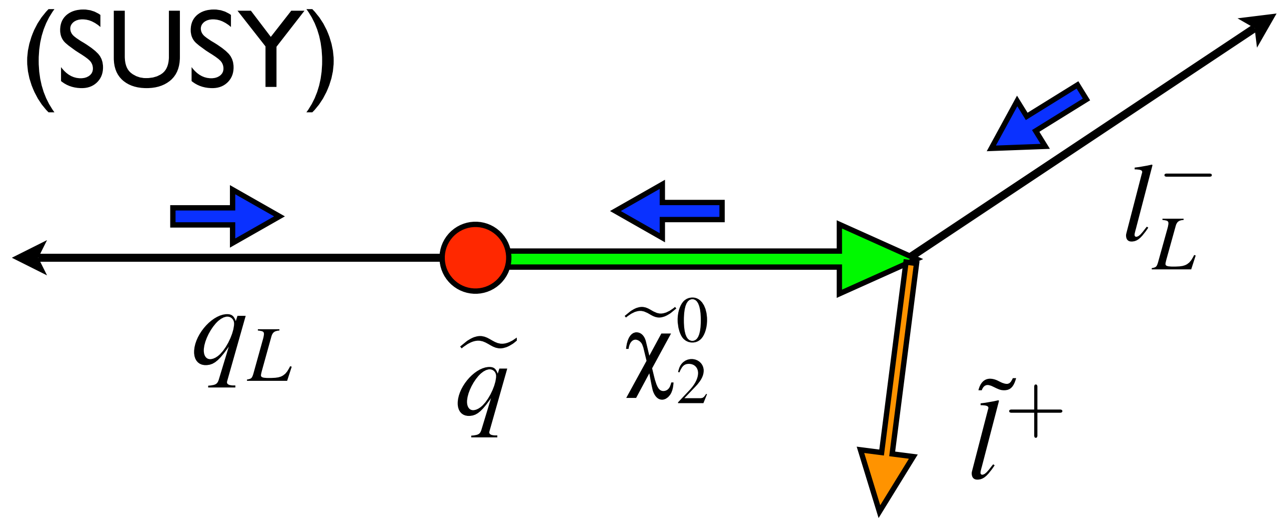
Invariant masses

- ql^{near}: $m_{ql}/(m_{ql})_{max} = \sin(\theta^*/2)$
- $l^{near}l^{far}$: $m_{ll}/(m_{ll})_{max} = \sin(\theta/2)$
- ql^{far}: $$m_{ql}/(m_{ql})_{max} = \frac{1}{2}\Big[(1-y)(1-\cos\theta^*\cos\theta)+ +(1-y)(\cos\theta^*-\cos\theta)-2\sqrt{y}\sin\theta^*\sin\theta\cos\phi\Big]^{\frac{1}{2}}$$

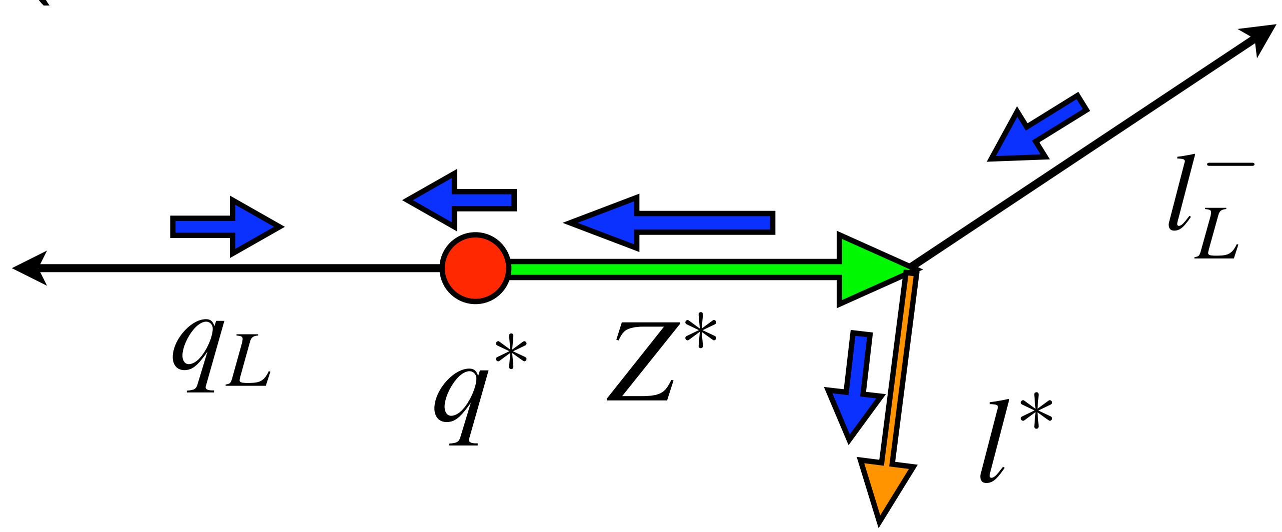
where $x = m_{Z^*}^2/m_{q^*}^2,\ y = m_{l^*}^2/m_{Z^*}^2,\ z = m_{\gamma^*}^2/m_{l^*}^2$

Helicity dependence

- Process I (SUSY)

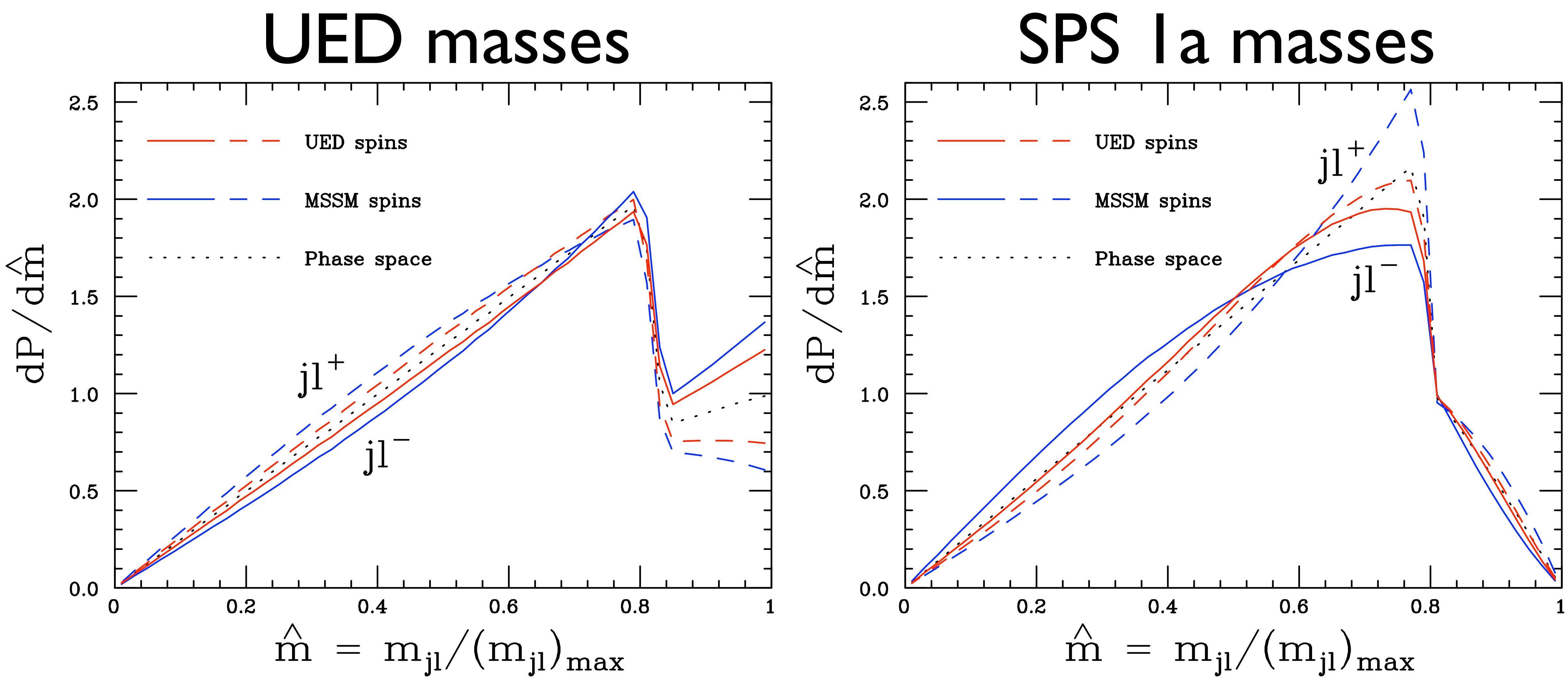


- Process I (UED, transverse Z*: $P_T/P_L = 2x$)



➡ Both prefer high $(ql^-)^{near}$ invariant mass

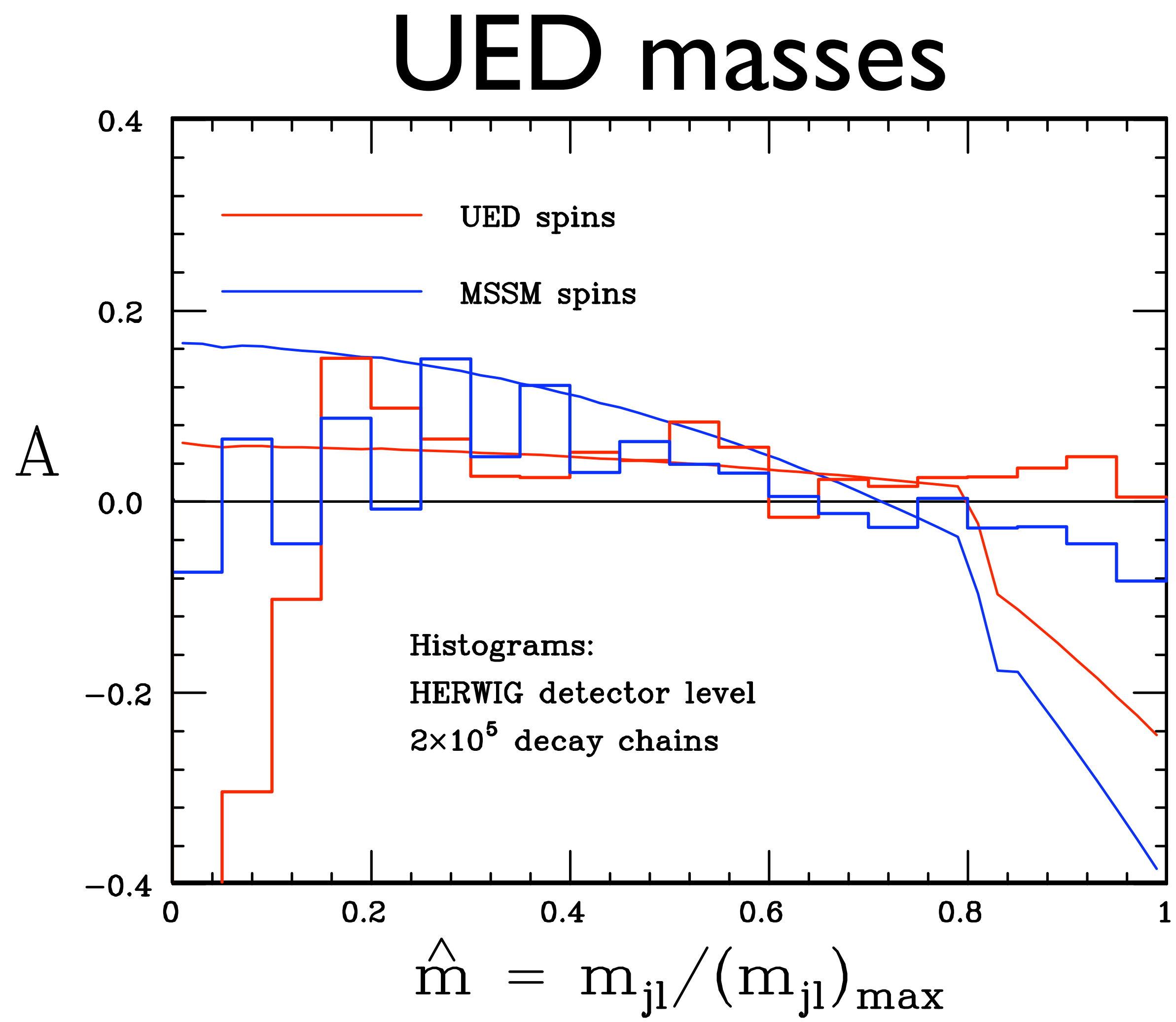
Jet + lepton mass distribution

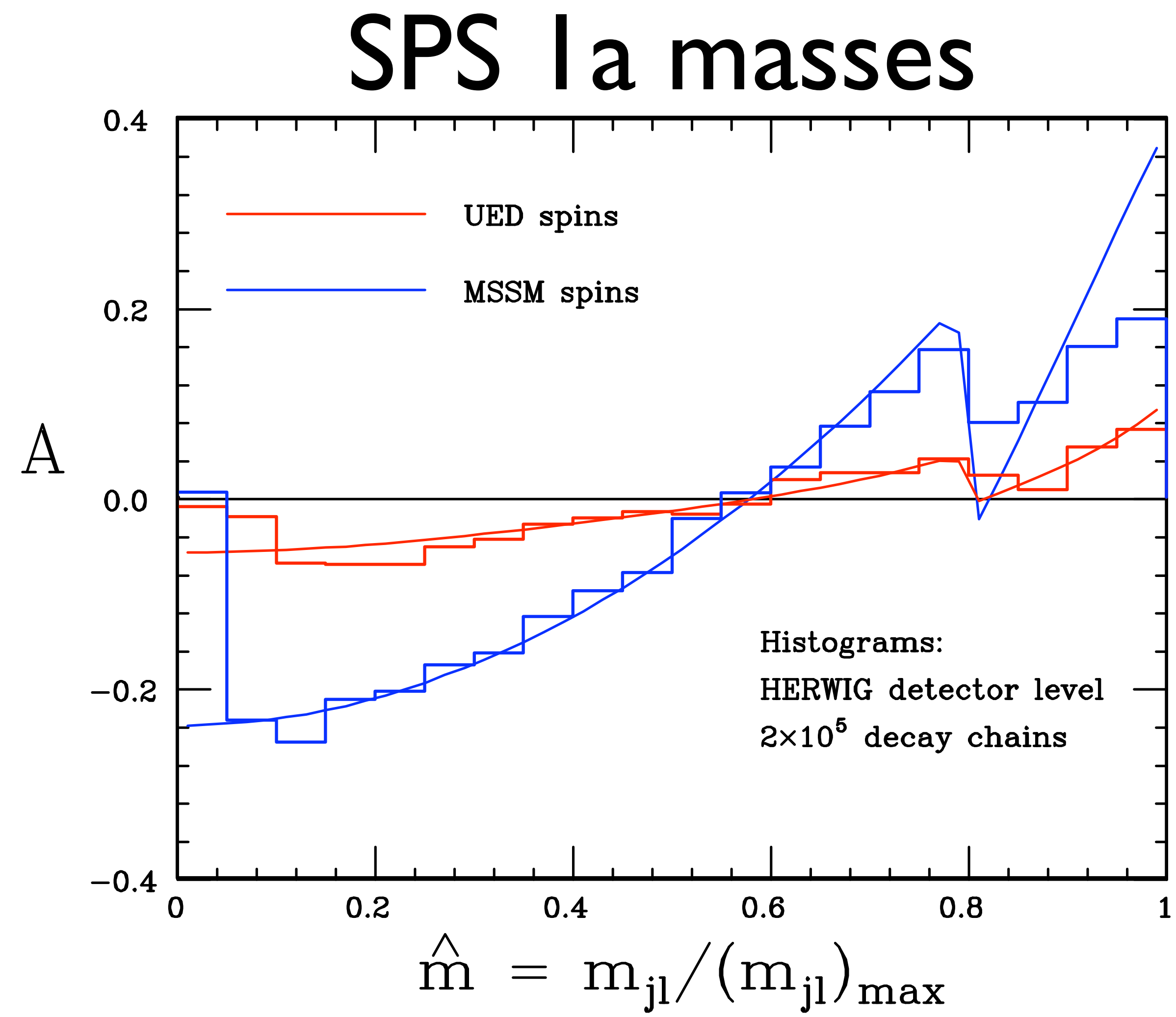


- Not resolvable for UED masses, maybe for SUSY masses
- Charge asymmetry due to quark vs antiquark excess

Charge Asymmetry

$$A = \frac{(jl^+) - (jl^-)}{(jl^+) + (jl^-)}$$

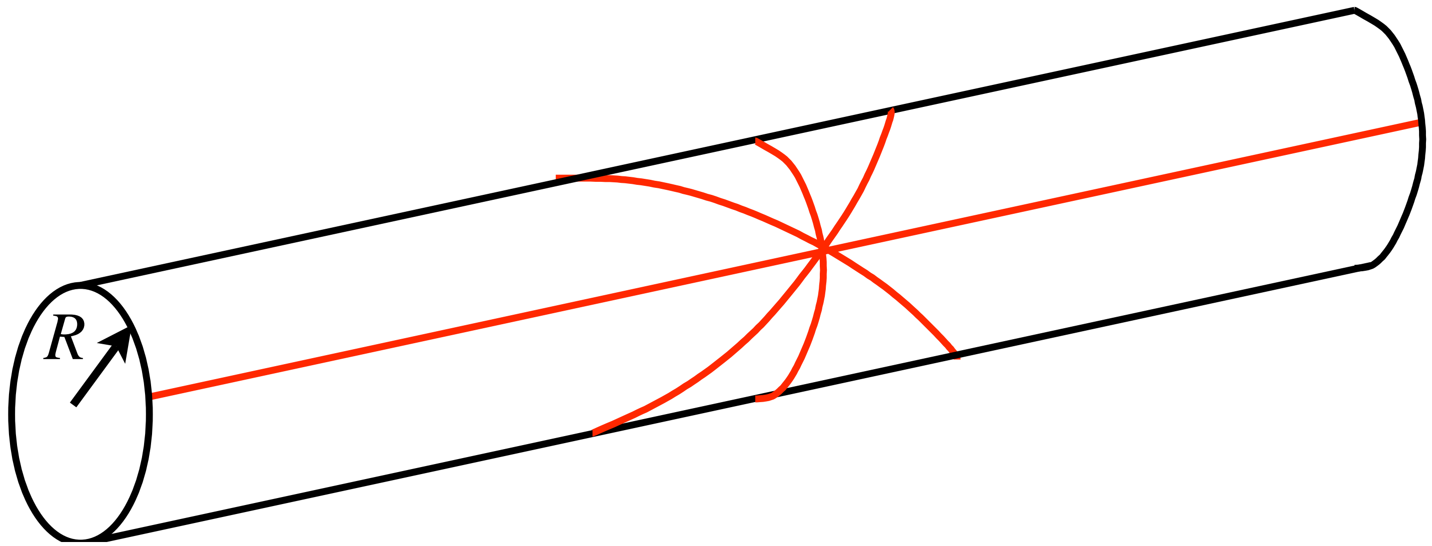




- Similar form, different magnitude
- Not detectable for UED masses

Black Holes at the LHC?

- For n extra dimensions compactified at scale R



$$F(r < R) \sim G_{4+n} \frac{m_1 m_2}{r^{2+n}}$$

$$F(r > R) \sim G_{4+n} \frac{m_1 m_2}{r^2 R^n}$$

$$\Rightarrow G_4 = \frac{G_{4+n}}{R^n}$$

TeV-Scale Gravity

$$G_4 = G_{4+n}/R^n$$

$$G_{4+n} = M_{PL}^{-2-n}$$

$$\Rightarrow M_{PL}^{(4)} = M_{PL}\left(\frac{M_{PL}c}{\hbar}R\right)^{n/2}$$

- Hence for $M_{PL} = 1$ TeV we need

$$10^{19}\ \mathrm{GeV} \sim 10^{3}\ \mathrm{GeV} \times (10^{4}\,R/\mathrm{fm})^{n/2}$$

➡ mm for n=2, nm for n=3, pm for n=4

Black hole production

- Parton-level cross section:

$$\hat{\sigma}(\hat{s} = M_{BH}^2) = F_n \pi r_S^2$$

- $r_S =$ Schwarzschild radius in 4+n dimensions:

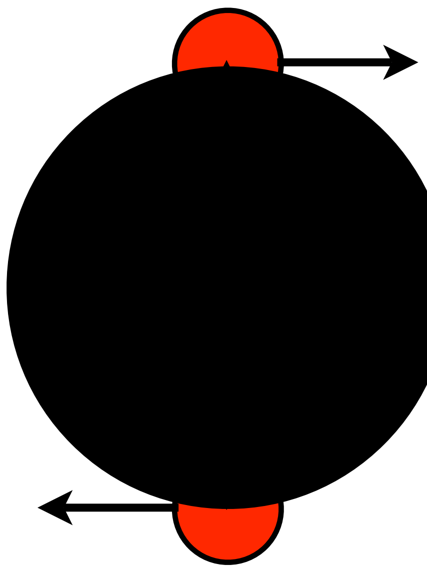
$$r_S = \frac{1}{\sqrt{\pi} M_{PL}} \left[\frac{8\Gamma\left(\frac{n+3}{2}\right) M_{BH}}{(n+2) M_{PL}} \right]^{\frac{1}{n+1}}$$

- $F_n =$ form factor of order unity (hoop conjecture)

- Usually set Planck scale $M_{PL} = 1$ TeV for illustration

(Dimopoulos-Landsberg $M_{PL} \equiv \left[G_{(4+n)}\right]^{-\frac{1}{n+2}}$)

BH formation factor (I)



$$b_{max} = 2r_h = 2r_s\left[1 + a_*^2\right]^{-\frac{1}{n+1}}$$

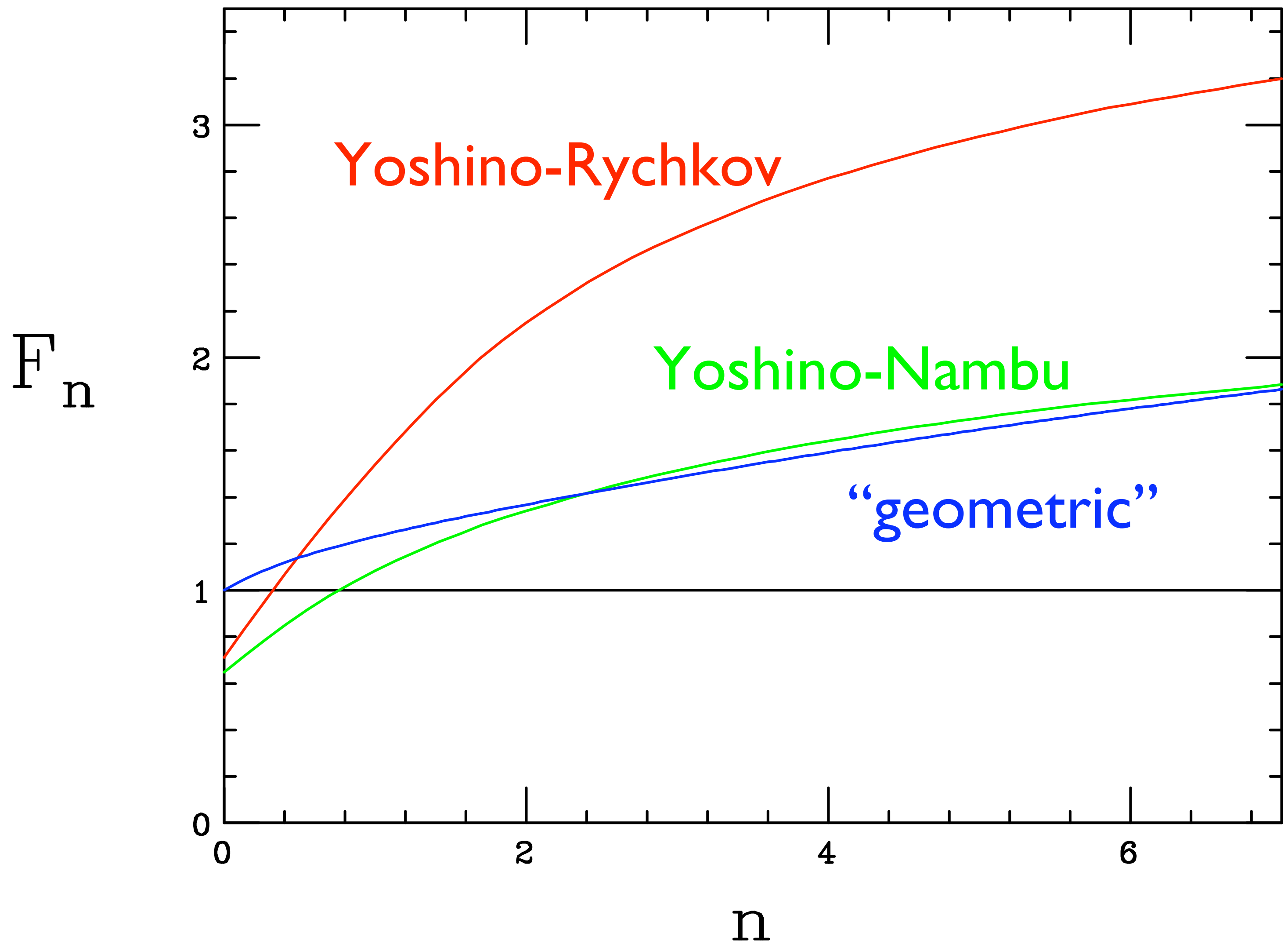
$$a_* = \frac{(n+2)J}{2r_h M_{BH}}\ , \quad J \simeq b M_{BH}/2$$

$$\hat{\sigma} = F_n \pi r_S^2 \simeq \pi b_{max}^2$$

$$\Rightarrow \quad F_n \simeq 4\left[1 + \left(\frac{n+2}{2}\right)^2\right]^{-\frac{2}{n+1}}$$

("geometric")

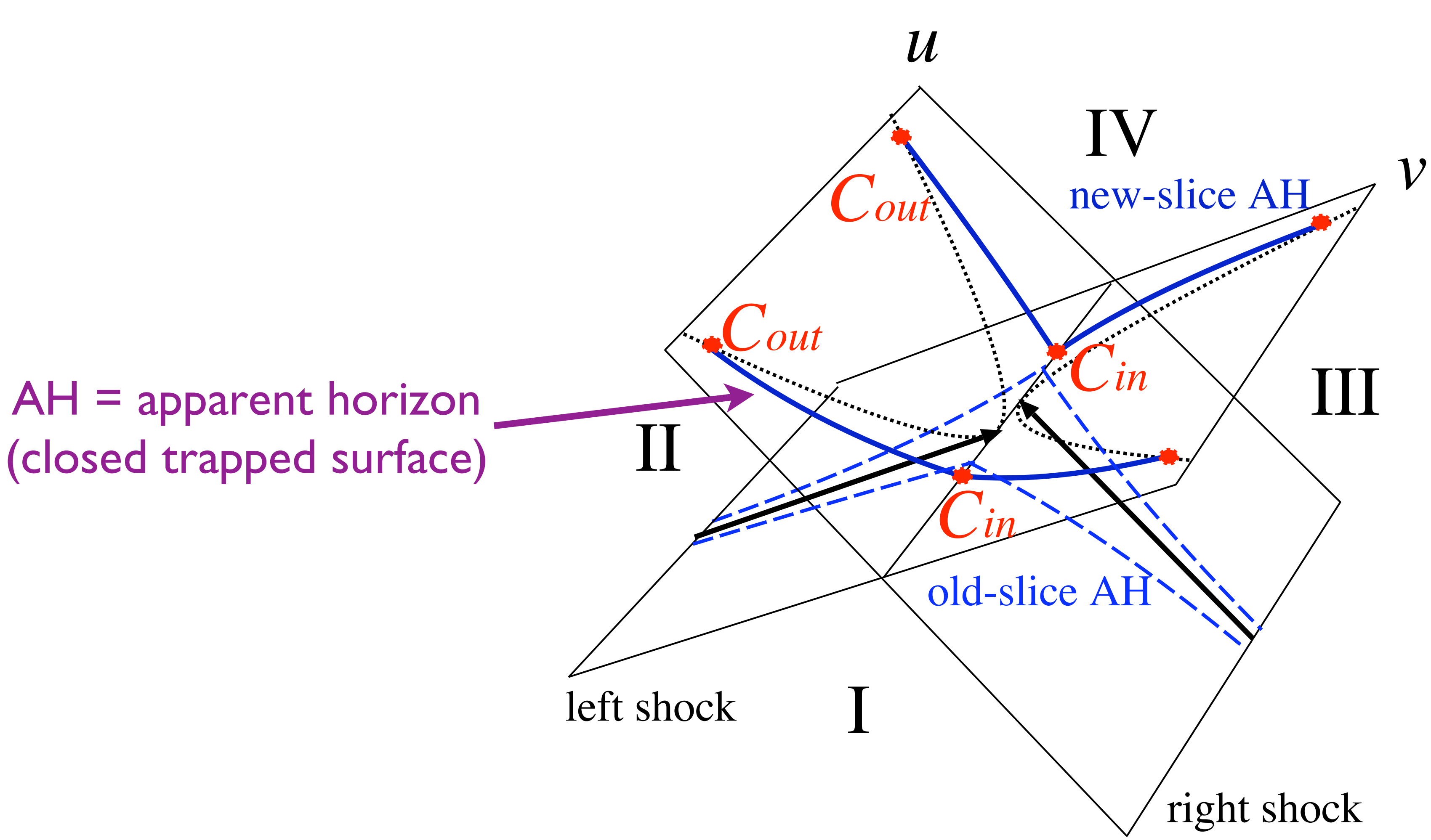
BH formation factor (2)



H Yoshino & Y Nambu, gr-qc/0209003

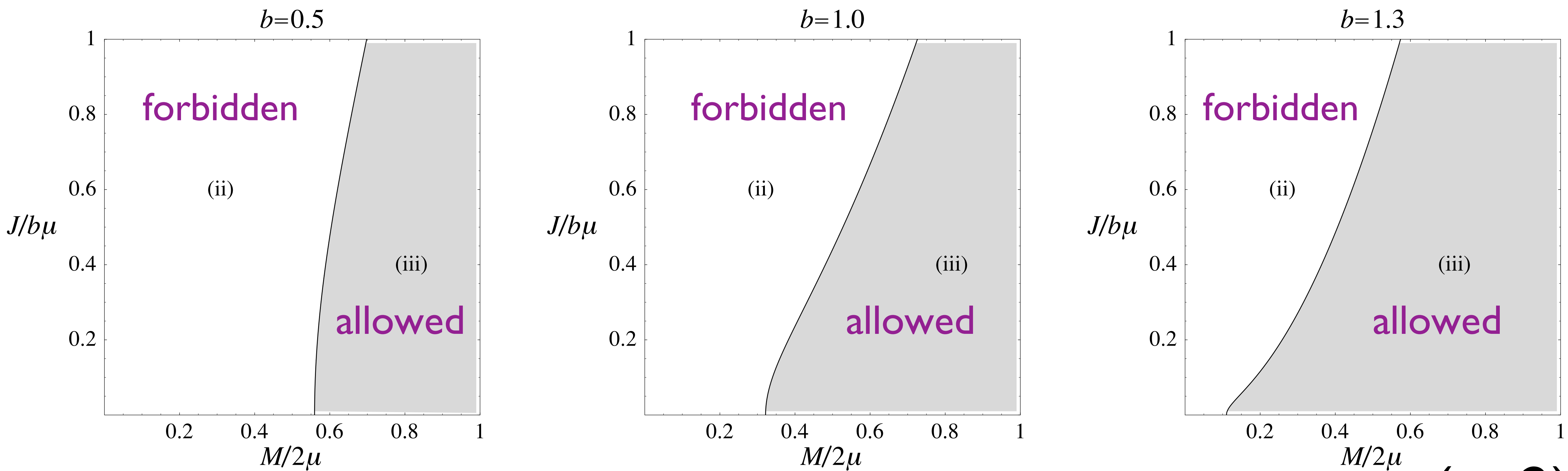
H Yoshino & VS Rychkov, hep-th/0503171

Yoshino-Rychkov Bound on $\hat{\sigma}_{BH}$



- YN bound is πb_{max}^2 for AH on past lightcone (boundary of region I)
- YR bound is πb_{max}^2 for AH on future lightcone (boundary of regions II & III)
- Area of AH sets limits on M_{BH} and J_{BH}

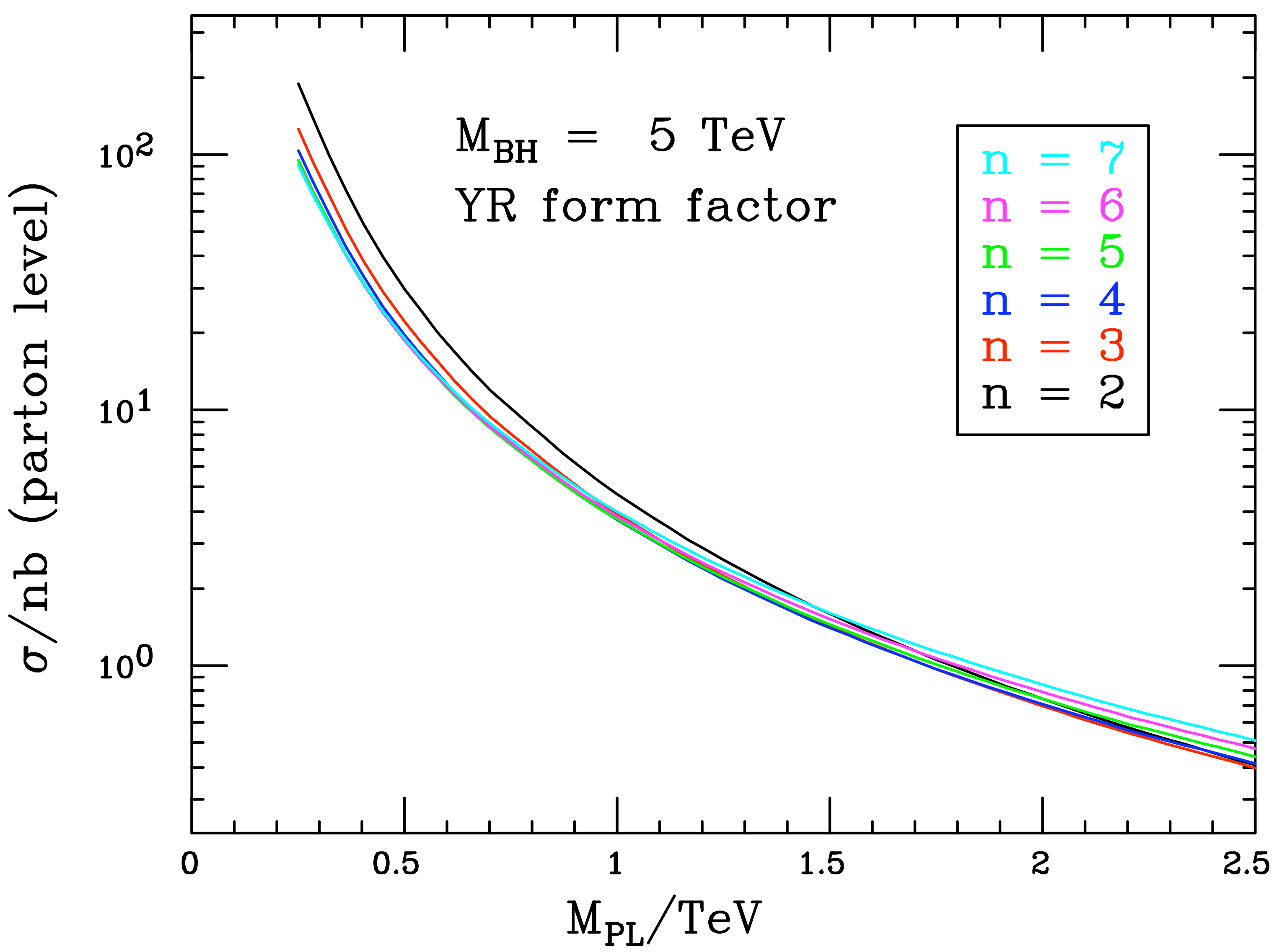
Limits on M_{BH} and J_{BH}



(n=2)

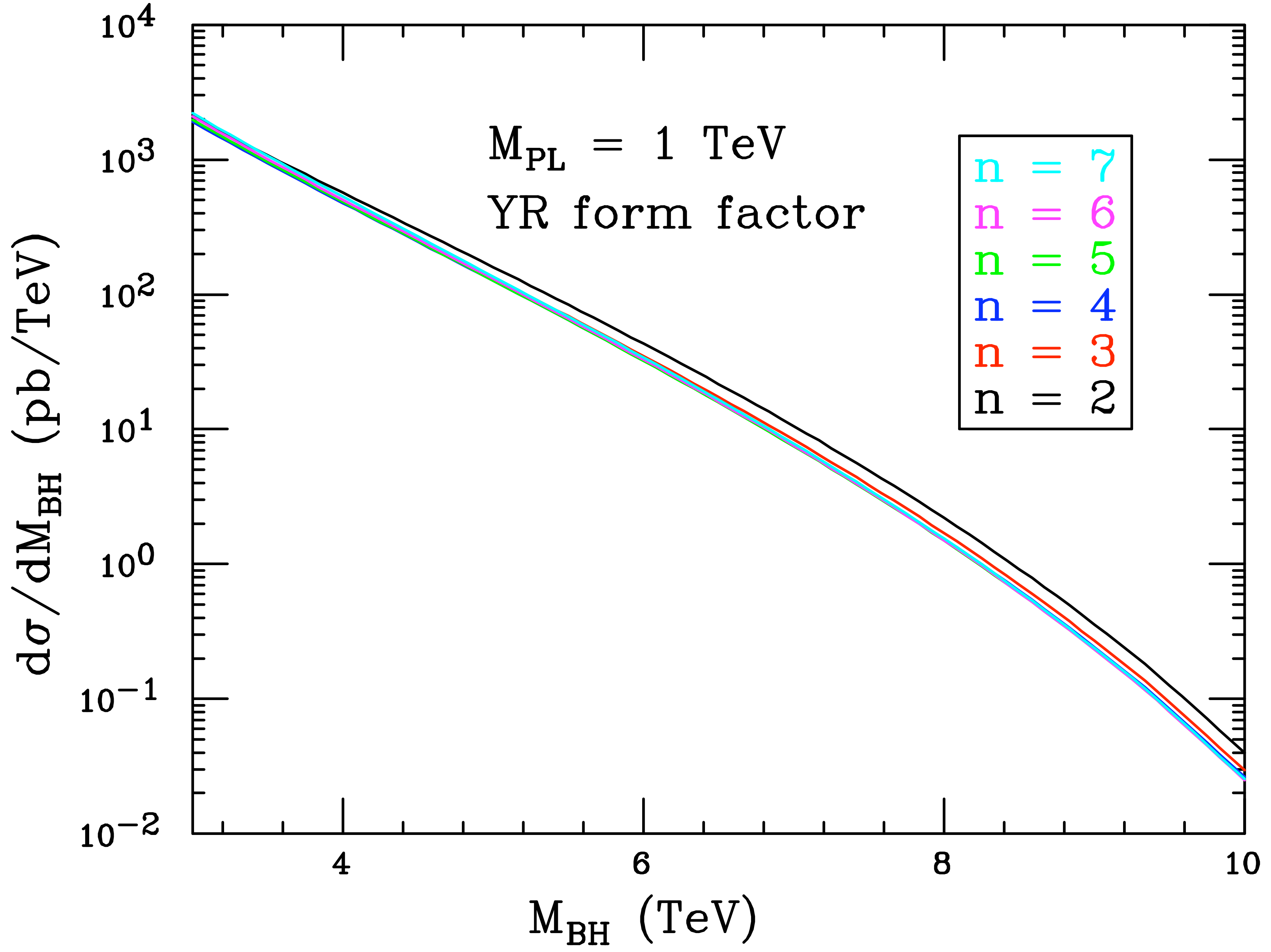
- $\mu \equiv \sqrt{\hat{s}}/2$, so $M/2\mu = 1$ implies $M_{BH}^2 = \hat{s}$
- We'll assume $M_{BH} \simeq 2\mu = \sqrt{\hat{s}}$, $J_{BH} \simeq b\mu \simeq bM_{BH}/2$

BH cross section vs Planck mass



- Little sensitivity to n
- Sensitive to assumption that $M_{BH} \simeq \sqrt{\hat{s}}$

BH cross sections at LHC



➡ Several 5 TeV BH per minute at LHC!

Black hole decay (1)

- Balding phase
  - ➔ loses `hair’ and multipole moments, mainly by gravitational radiation
- Spin-down phase
  - ➔ loses angular momentum, mainly by Hawking radiation
- Schwarzschild phase
  - ➔ loses mass by Hawking radiation, temperature increases
- Planck phase
  - ➔ mass and/or temperature reach Planck scale: remnant = ??

Black hole decay (2)

- We'll assume Schwarzschild phase is dominant
  - all types of SM particles emitted with Hawking spectrum

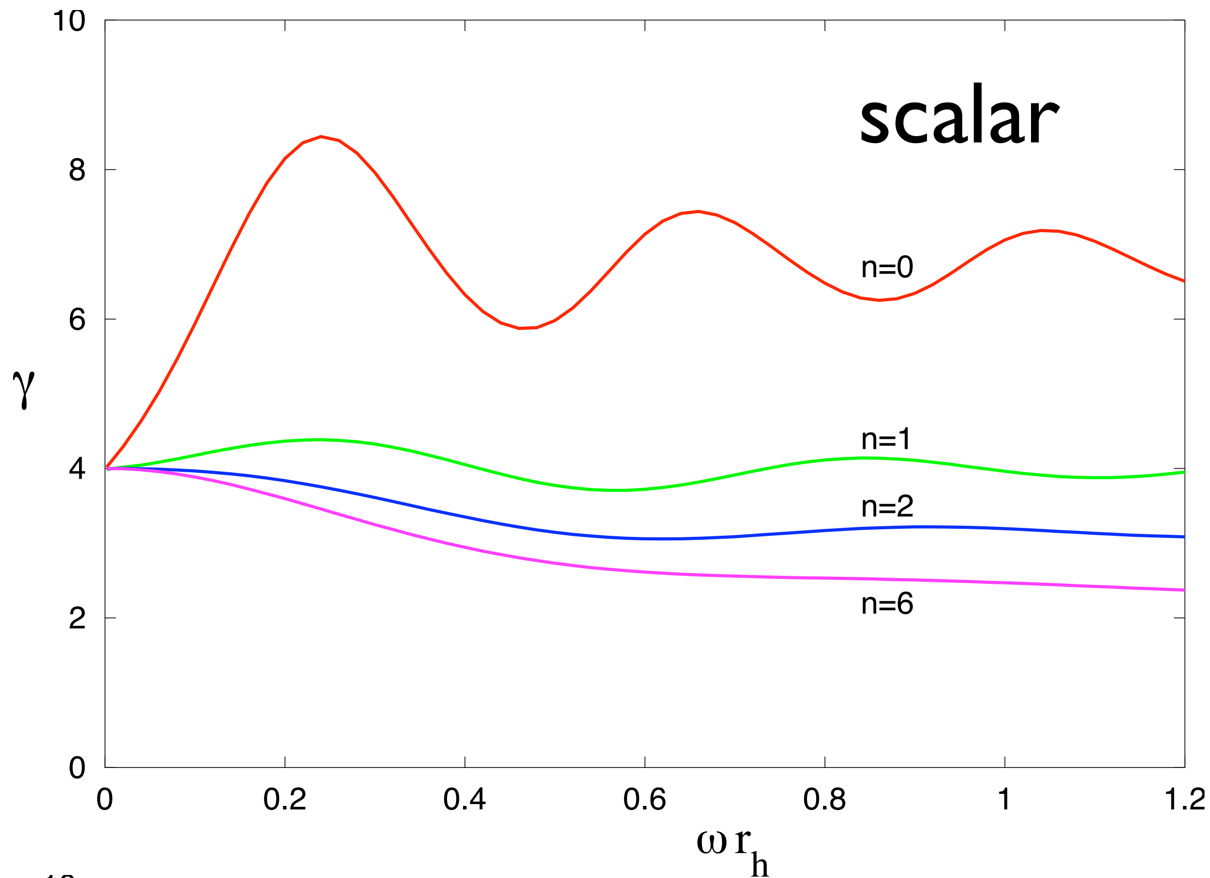
$$\frac{dN}{dE} \propto \frac{\gamma E^2}{(e^{E/T_H} \mp 1)T_H^{n+6}}$$

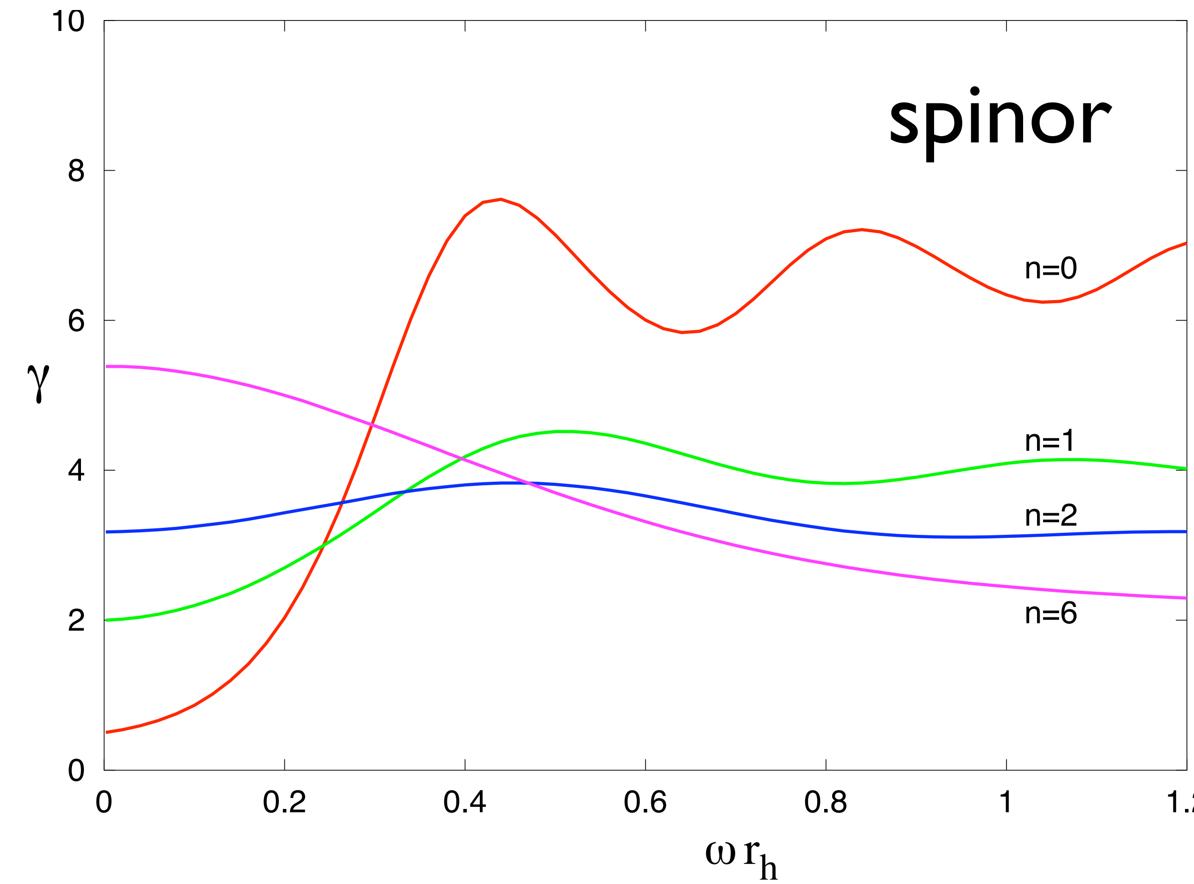
  - Hawking temperature

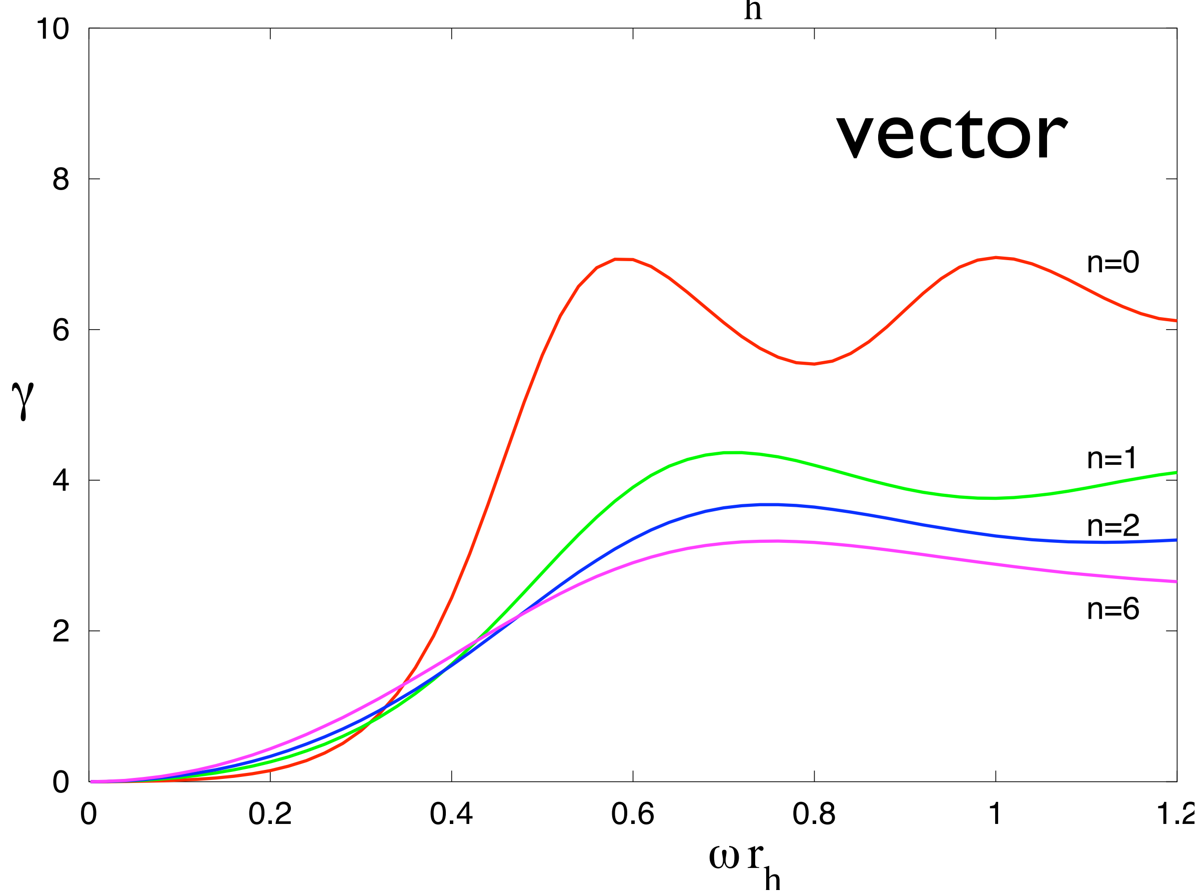
$$T_H = \frac{n+1}{4\pi r_{BH}} \propto (M_{BH})^{-\frac{1}{n+1}}$$

  - γ is (4+n)-dimensional grey-body factor

Grey-body factors

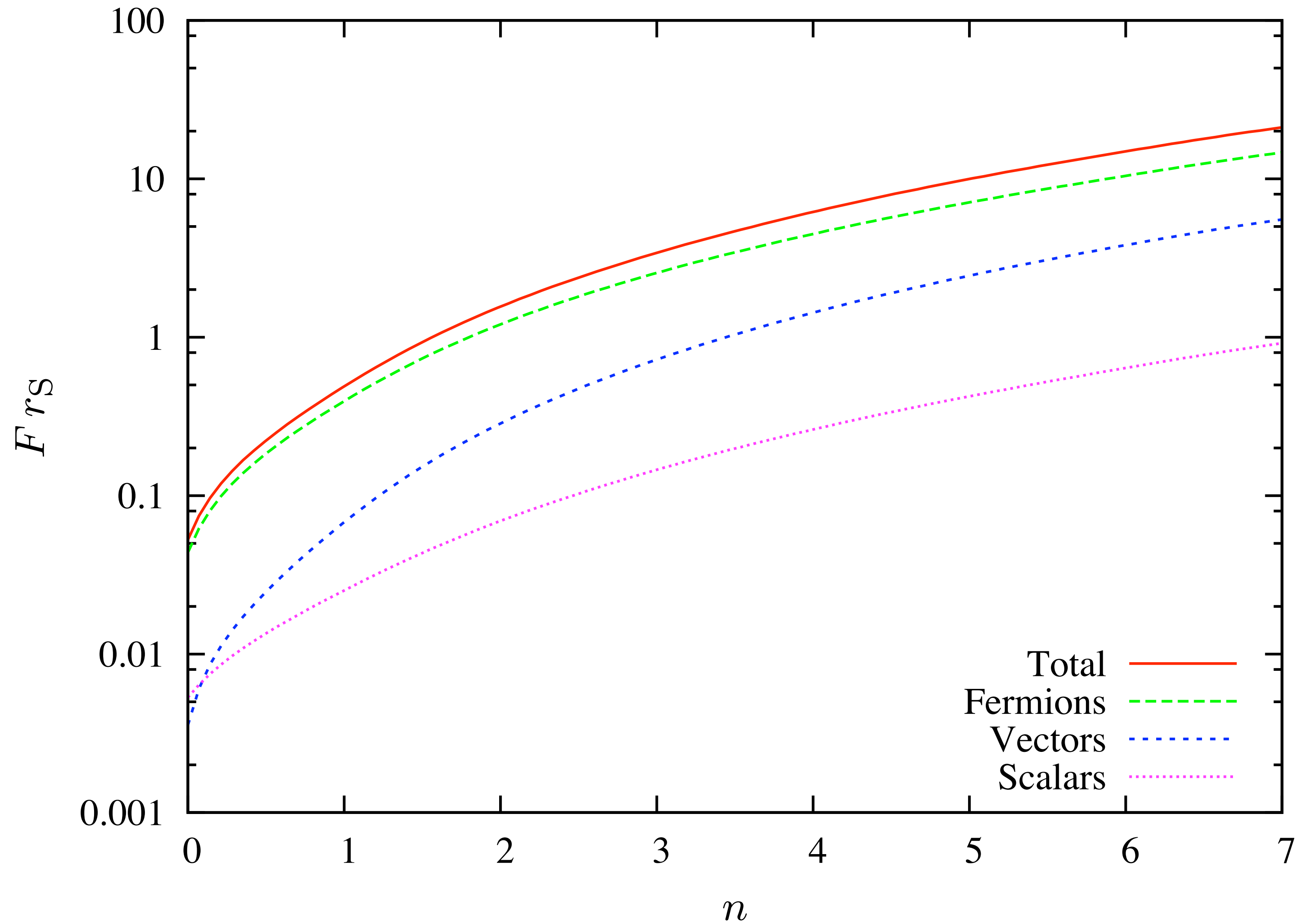






- Emission on brane only
- Low-energy vector suppression
- CM Harris, hep-ph/0502005

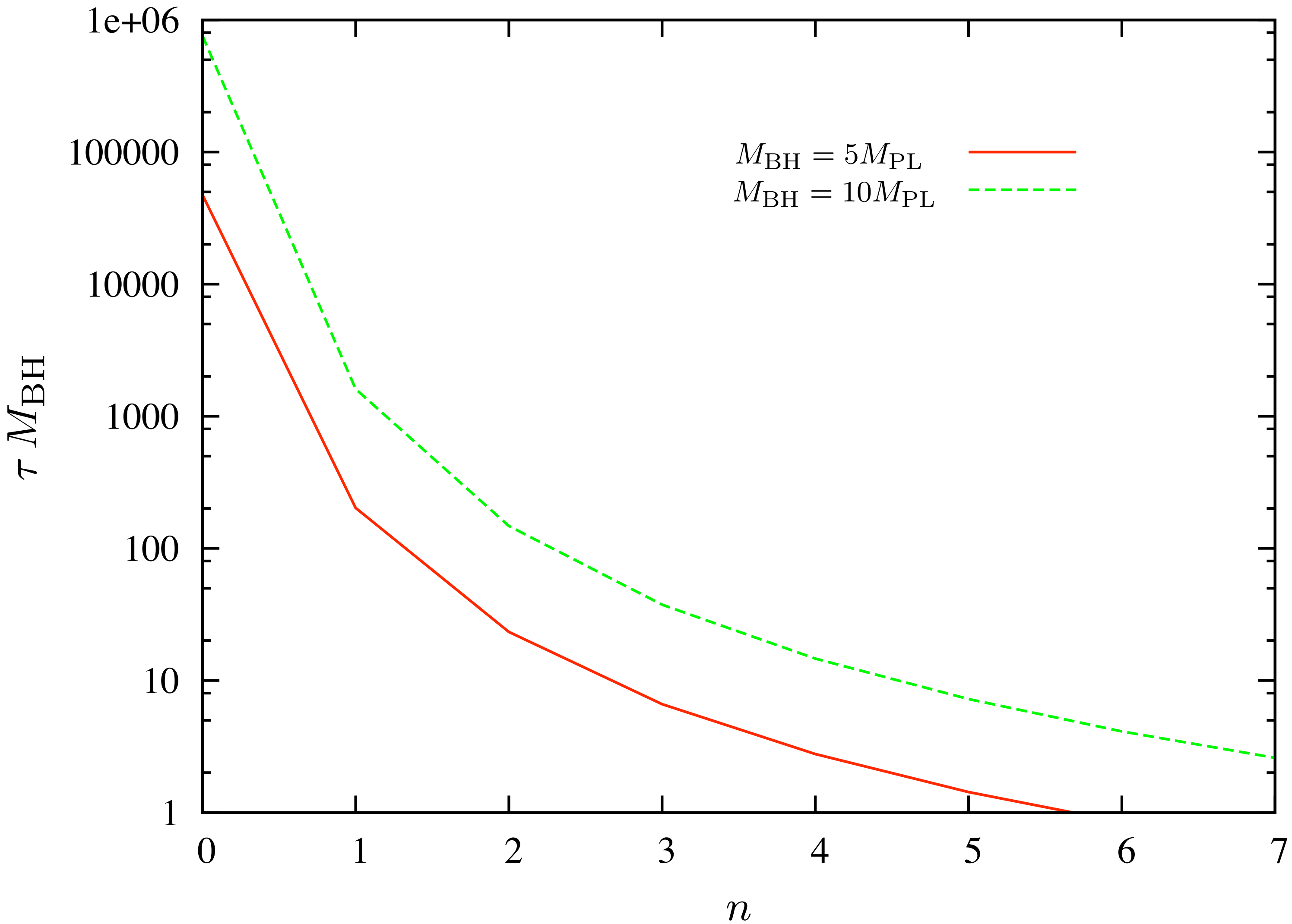
Integrated Hawking flux



N.B. $F^{tot} r_s \gg 1$ at large n

- Transit time $\gg$ time between emissions
- Decay no longer quasi-stationary at large n

Black hole lifetime



$$\left(M_{\rm BH} = 5\ {\rm TeV} \Rightarrow M_{\rm BH}^{-1} \sim 10^{-28}\ {\rm s}\right)$$

N.B. $\tau M_{\rm BH} \sim 1$ at large n

➡ Black hole no longer well-defined?

Black Hole Event Generators

- TRUENOIR (Dimopoulos & Landsberg, hep-ph/0106295)
  - ➡ J=0 only; no energy loss; fixed T; no g.b.f.
- CHARYBDIS (Harris, Richardson & BW, hep-ph/0307305)
  - ➡ J=0 only; no energy loss; variable T; g.b.f. included
- CATFISH (Cavaglia et al., hep-ph/0609001)
  - ➡ J=0 only; energy loss option; variable T; g.b.f. included

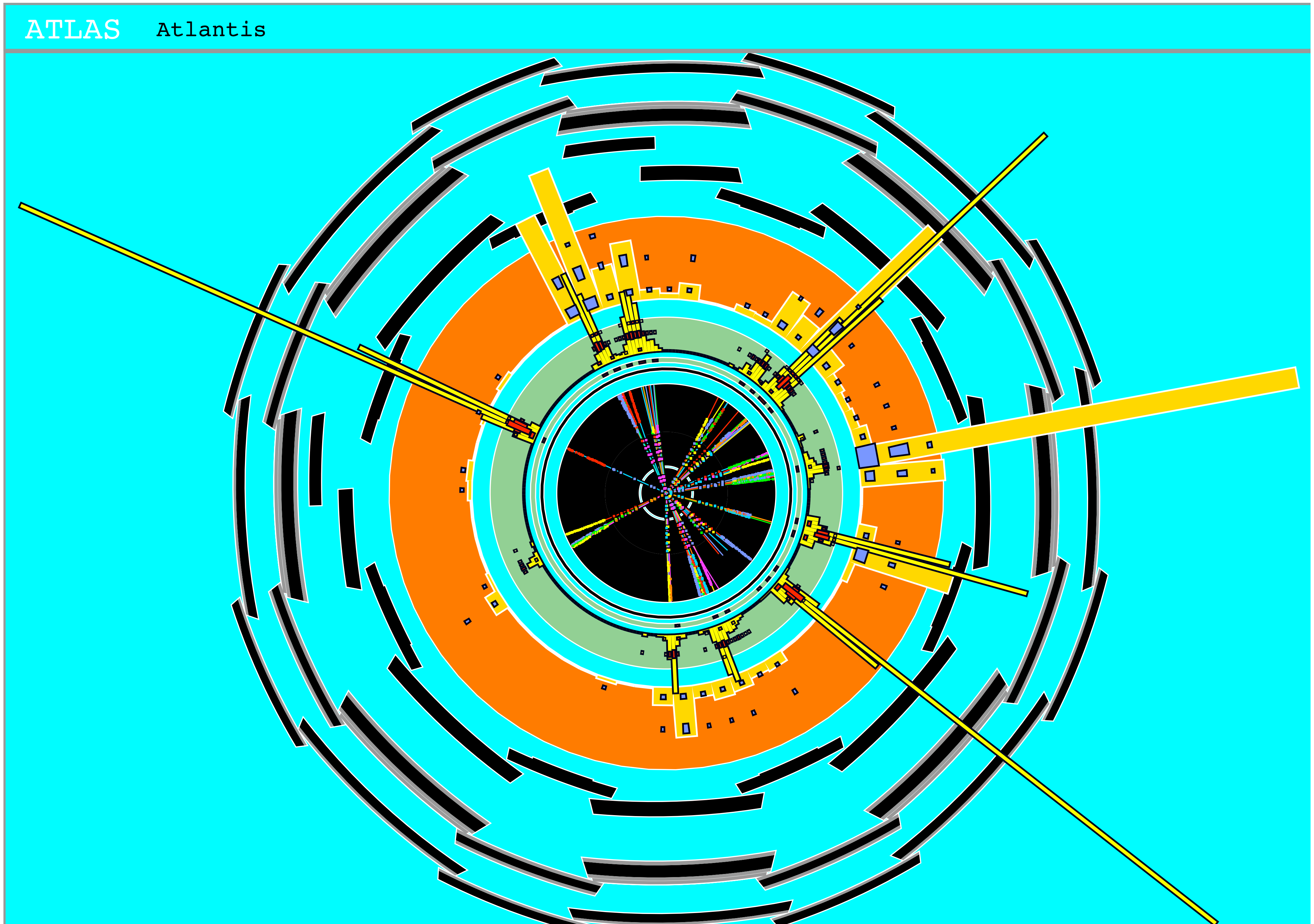
➡ All need interfacing to a parton shower and hadronization generator (PYTHIA or HERWIG)

Main CHARYBDIS parameters

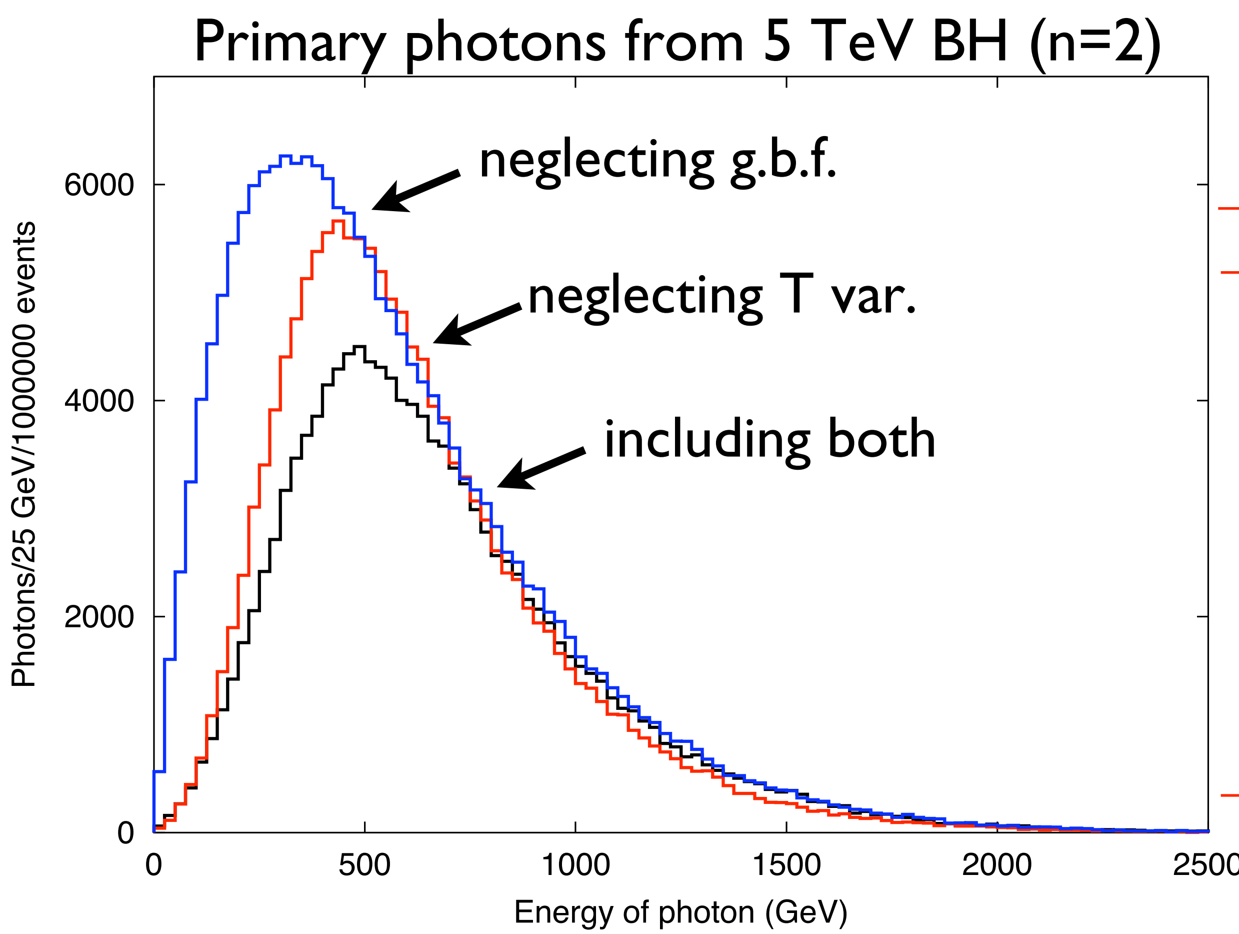
Name	Description	Values	Default
TOTDIM	Total dimension (n+4)	6-11	6
MPLNCK	Planck mass (GeV)	real	1000
GTSCA	Use scale ($1/r_S$) not M_{BH}	logical	.FALSE.
TIMVAR	Use time-dependent T_H	logical	.TRUE.
MSSDEC	Include t,W,Z(2), h(3) decay	1-3	3
GRYBDY	Include grey-body factors	logical	.TRUE.
KINCUT	Use kinematic cutoff	logical	.TRUE.

CHARYBDIS Event at LHC

TOTDIM = 10 MPLNCK = 1 TeV M_{BH} = 8 TeV



Effects of grey-body factors



	Particle emissivity (%)			
	GRYBDY=.TRUE.		GRYBDY=.FALSE.	
Particle type	Generator	Theory	Generator	Theory
Quarks	63.9	61.8	58.2	56.5
Gluons	11.7	12.2	16.9	16.8
Charged leptons	9.4	10.3	8.4	9.4
Neutrinos	5.1	5.2	4.6	4.7
Photon	1.5	1.5	2.1	2.1
Z^0	2.6	2.6	3.1	3.1
W^+ and W^-	4.7	5.3	5.7	6.3
Higgs boson	1.1	1.1	1.0	1.1

- Vector boson suppression 20-30%
- Generator-theory differences due to masses & charge conservation

Exploring Higher Dimensional Black Holes at the Large Hadron Collider

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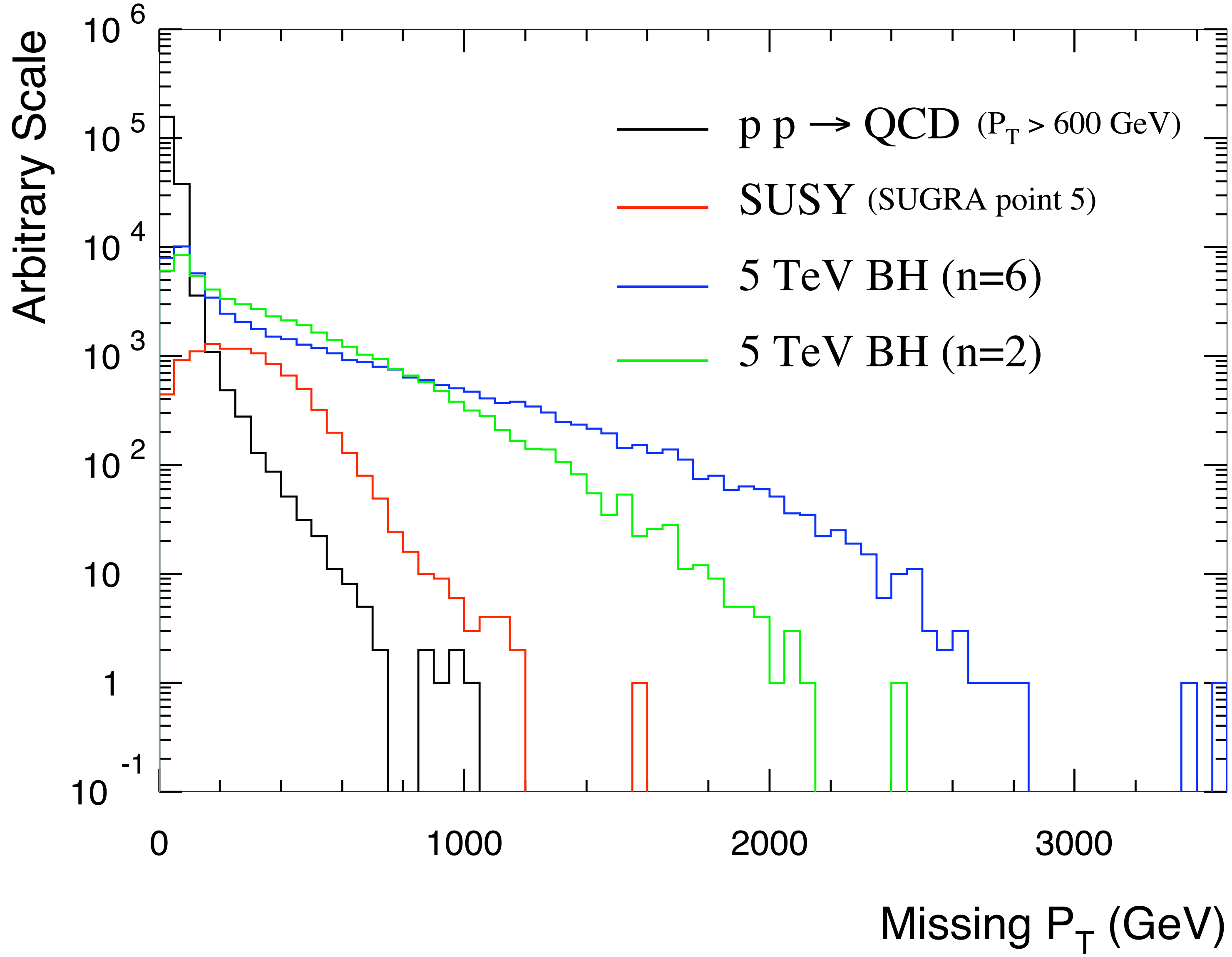
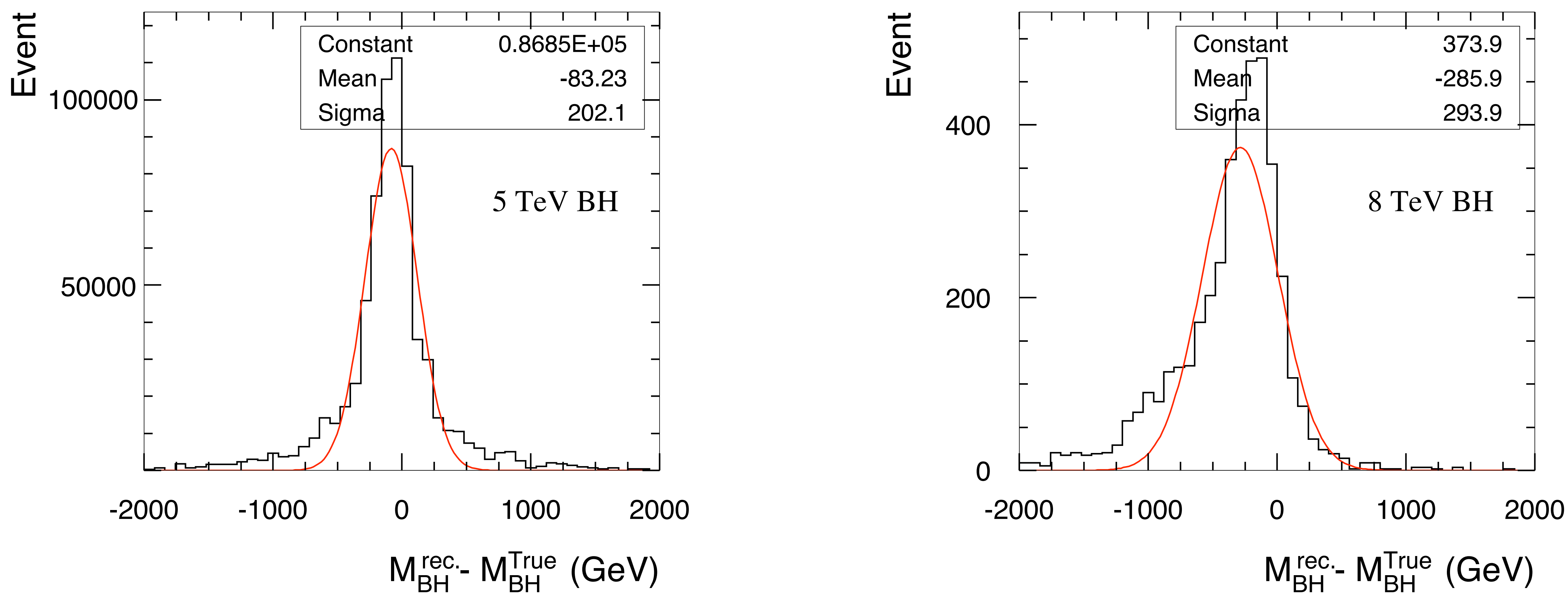
- hep-ph/0411022, JHEP05(2005)053; see also CM Harris, PhD thesis, hep-ph/0502005; CM Harris et al (CHARYBDIS event generator) hep-ph/0307035, JHEP08(2003)033
- earlier work: SB Giddings & S Thomas, hep-ph/0106219; S Dimopoulos & G Landsberg, hep-ph/0106295

Missing transverse energy



➡ Typically larger $\not{E}_T$ than SM or even MSSM

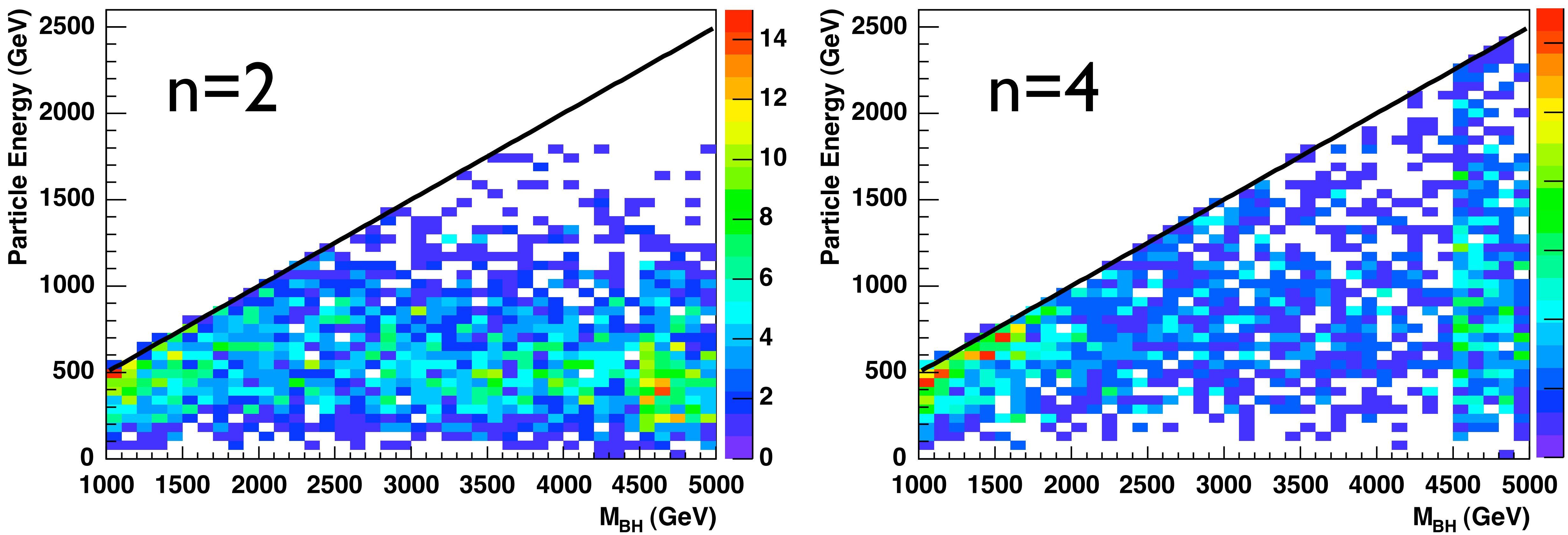
Measuring black hole masses



- Need $\not{E}_T < 100$ GeV for adequate resolution

➡ $\Delta M_{BH}/M_{BH} \sim 4\%$

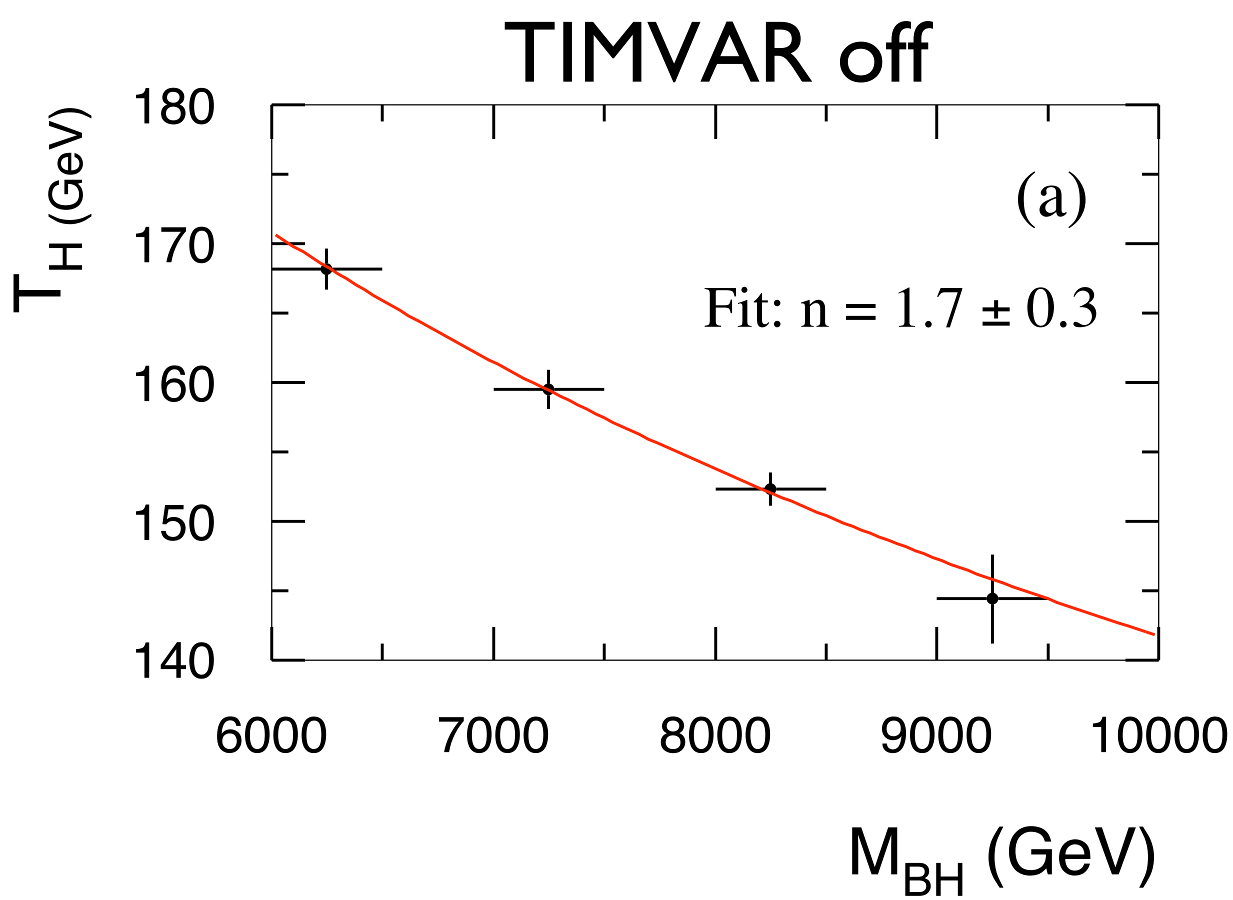
Effect of energy cutoff $E < M_{BH}/2$

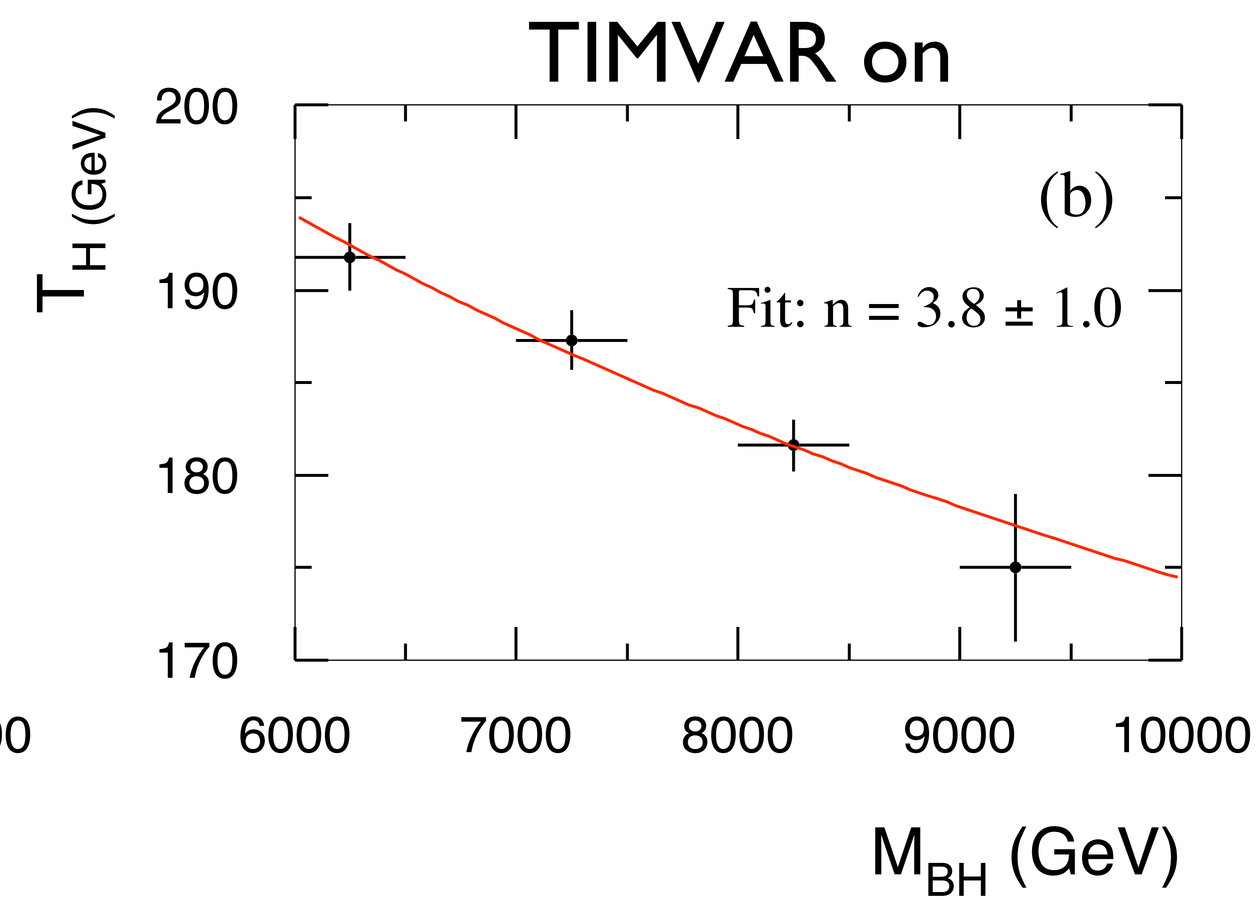


Energy distribution of primary emissions vs M_{BH}

➡ Cutoff affects spectrum at low mass and/or high n

Effects of time dependence

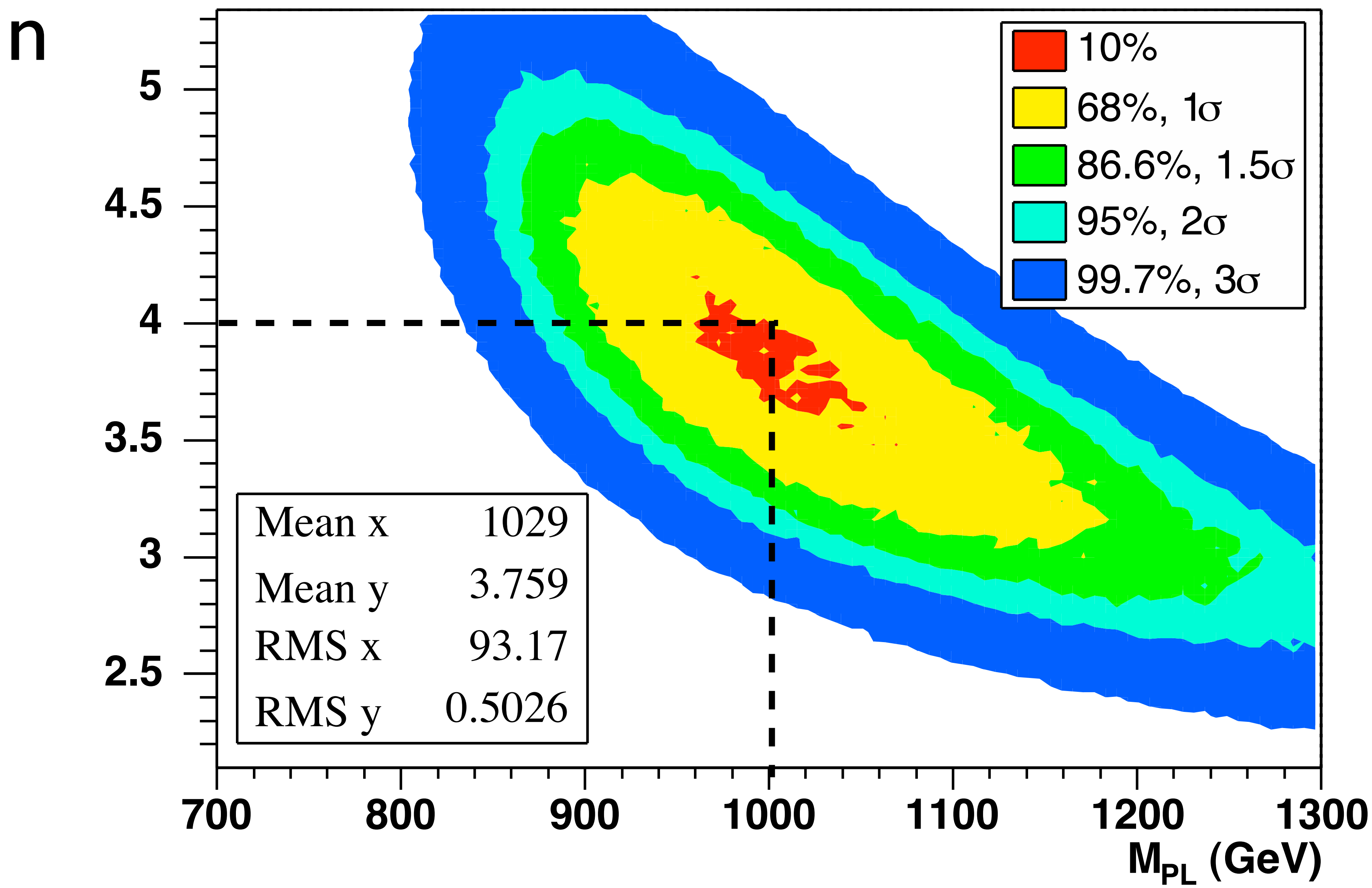




Fits to primary electron spectrum for n=2

➡ Neglecting time variation of T_H leads to over-estimate of n

Combined measurement of M_{PL} and n



➡ $\Delta M_{PL} / M_{PL} \sim 15\%$, $\Delta n \sim 0.75$

Conclusions

- Several event generators available for LHC
- Starting to describe multijets better
- (Slow) progress on matching to NLO
- Simulations of BSM scenarios also necessary
- Need spin correlations to confirm SUSY
- Black holes are a fun option (for now)
- LHC will tell!