New Horizon in Particle Physics

Workshop for Future Particle Accelerators

4 ~ 19 July 2019 KAIST, Daejeon, Republic of Korea

QCD at future colliders

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  - better knowledge of QCD parameters (α_S, m_{top}, PDFs, …) and of QCD dynamics will be required, to reduce systematic uncertainties
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- Several aspects of QCD dynamics are still obscure (exotic spectroscopy, high-density/high-T), and their exploration with future colliders will be needed to shed more light

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- **e^+e^-**
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  - Ditto for higher-E, except for the tt threshold, where QCD dynamics is crucial to extract m_{top} from the line shape
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  - Precise PDF determinations, crucial for the pp precisions programme
- **hh**
  - huge lever arm in Q^2 :
    - running of α_S, α_W => sensitive to heavy particles in the β function
    - exploration of BSM phenomena
  - immense rates
    - potential for precision measurements (eg of Higgs properties), provided QCD systematics is under control
  - heavy ion collisions, QCD at high T and density

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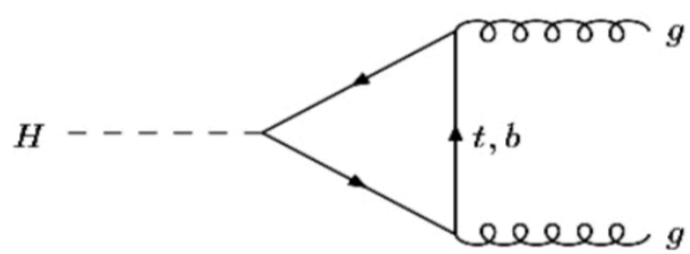
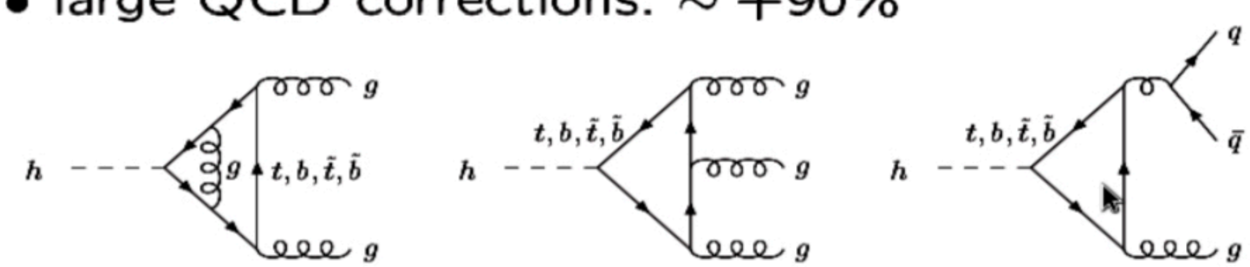
example



$BR(H \to gg) \sim 8\%$

- large QCD corrections: $\sim +90\%$

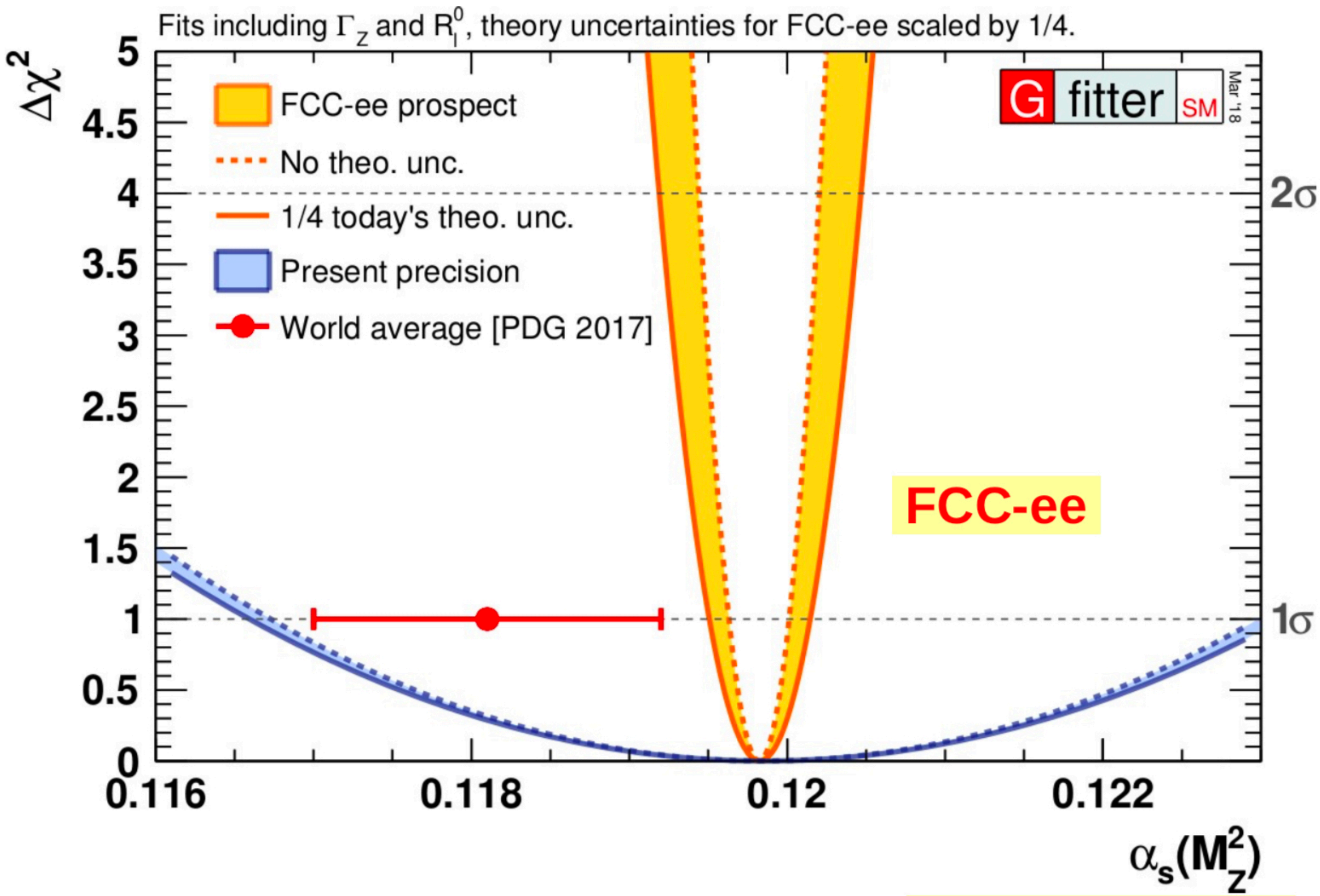
Inami, Kubota, Okada
S., Djouadi, Graudenz, Zerwas



$$\Gamma\,(H \to gg) \approx \Gamma_{LO}\,\{1 + 0.67 + 0.20 + 0.02\}$$

α_S from hadronic Z decays

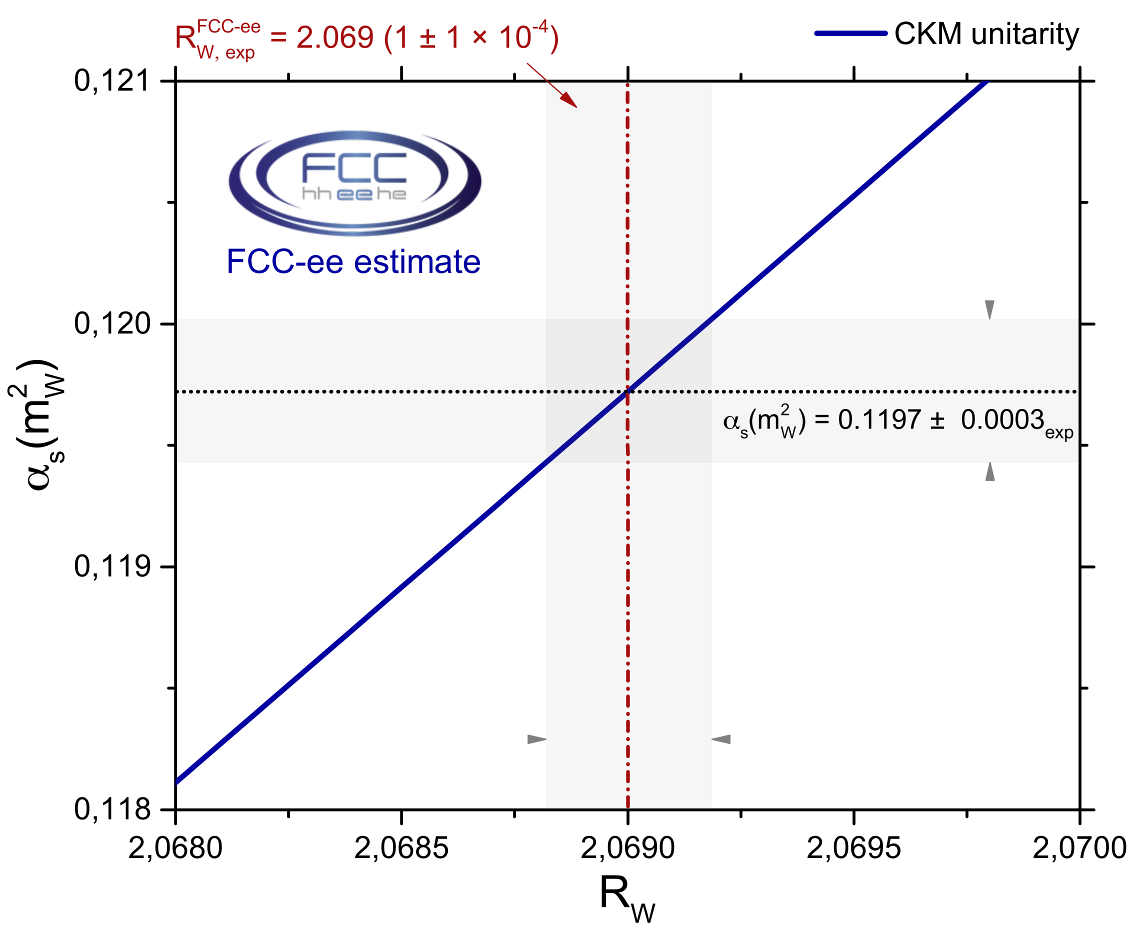
Global fit to 3 quantities: $R_\ell^0 = \frac{\Gamma_{\rm had}}{\Gamma_\ell}$, $\sigma_{\rm had}^0 = \frac{12\pi}{m_Z}\frac{\Gamma_e\Gamma_{\rm had}}{\Gamma_Z^2}$, $\sigma_\ell^0 = \frac{12\pi}{m_Z}\frac{\Gamma_\ell^2}{\Gamma_Z^2}$



10^{12} Z^0 => $\delta\alpha_S/\alpha_S < 0.2\%$

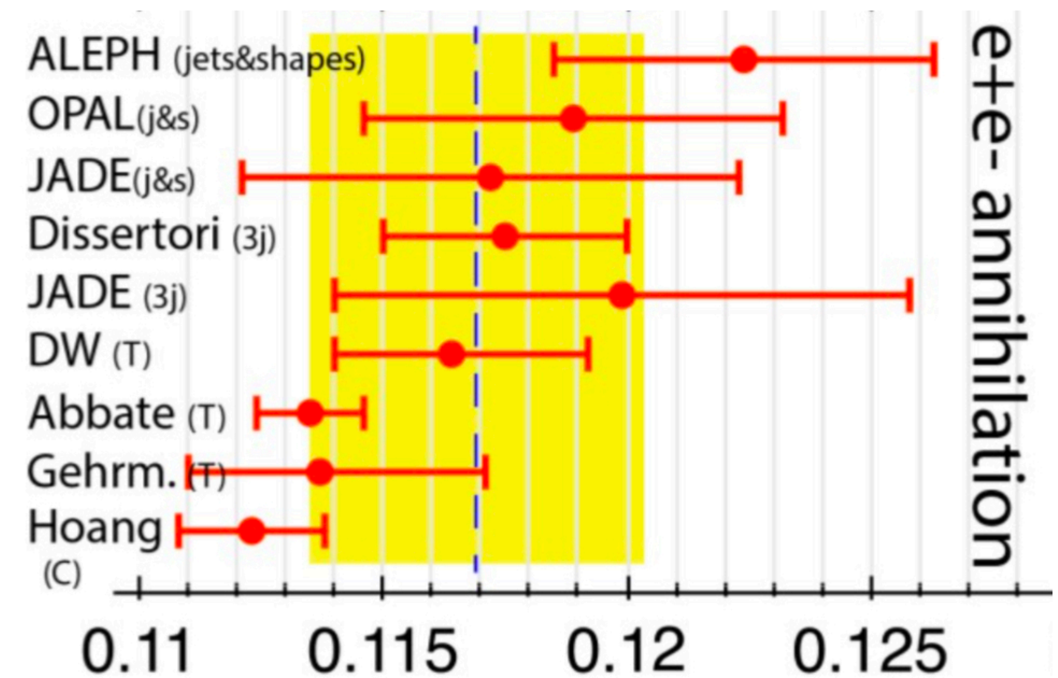
Further handles on α_s in ee

Γ_W^{had}



10^8 W => $\delta\alpha_s/\alpha_s \sim 0.3\%$

event shapes



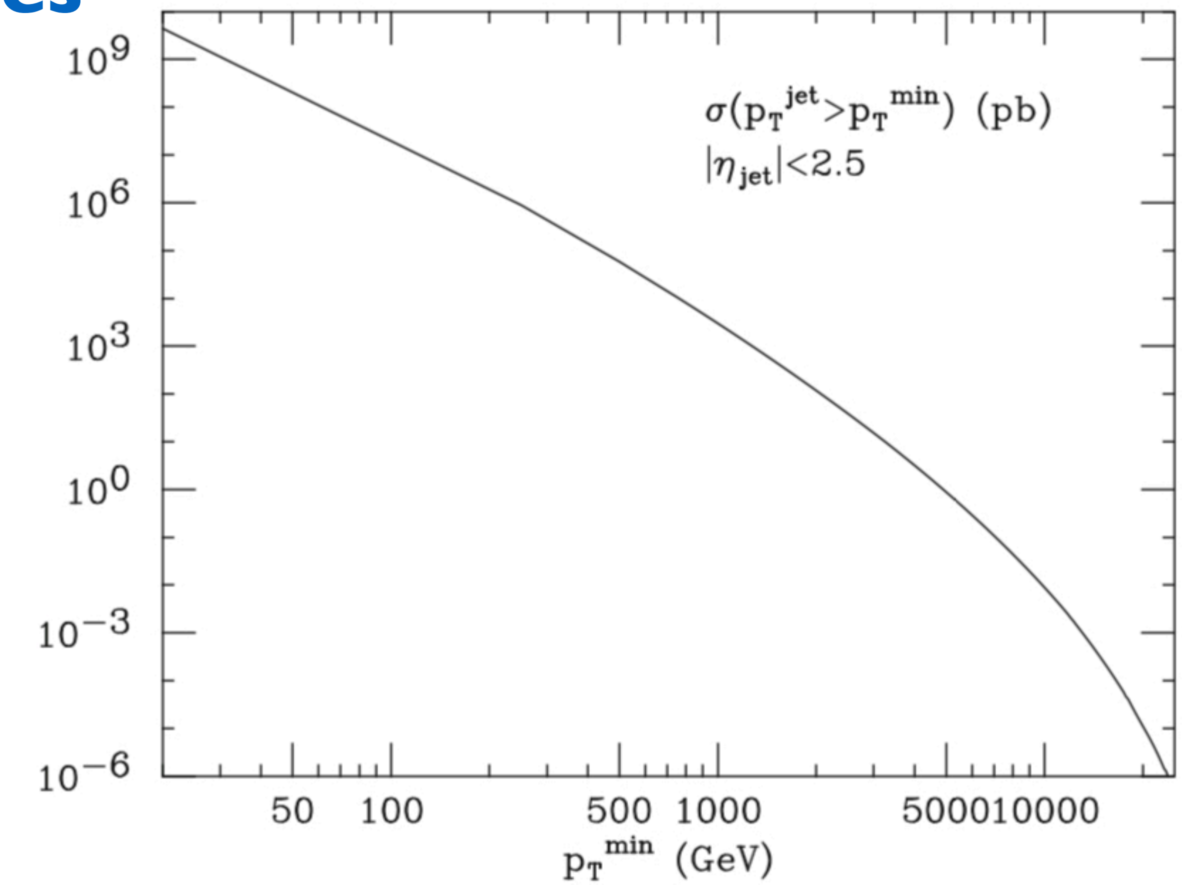
LEP: $\delta\alpha_s/\alpha_s \sim 2.9\%$

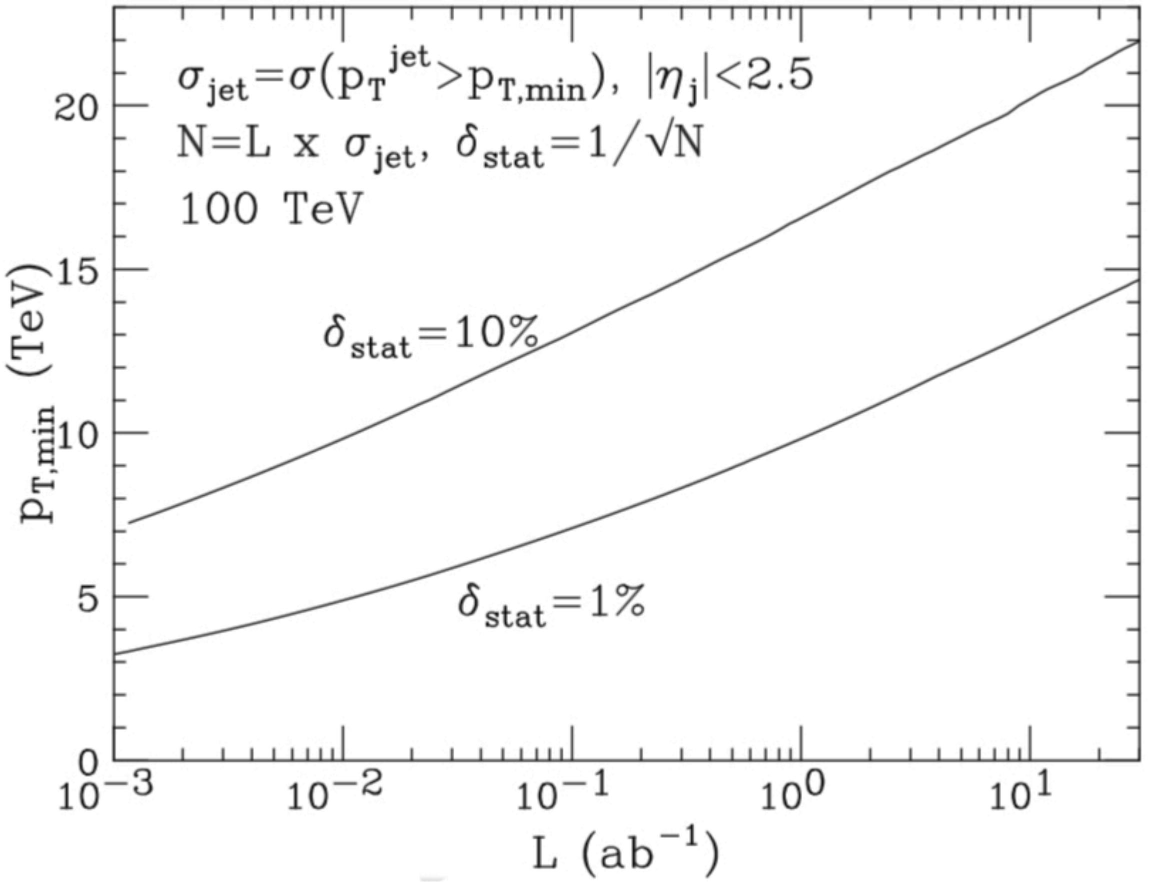
FCC-ee: $\delta\alpha_s/\alpha_s < 1\%$

limited by TH systematics on PT and non-PT corrections

α_S running at FCC-hh

Jet rates





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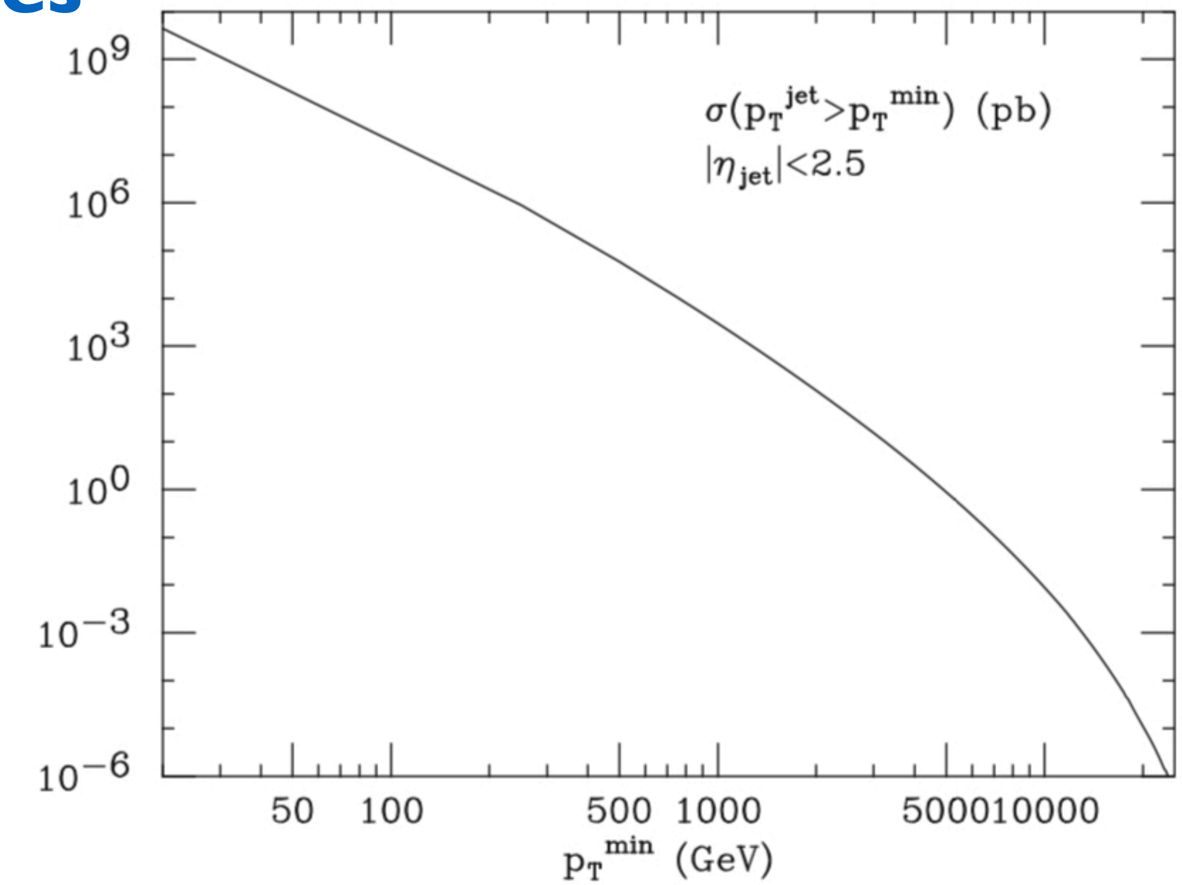
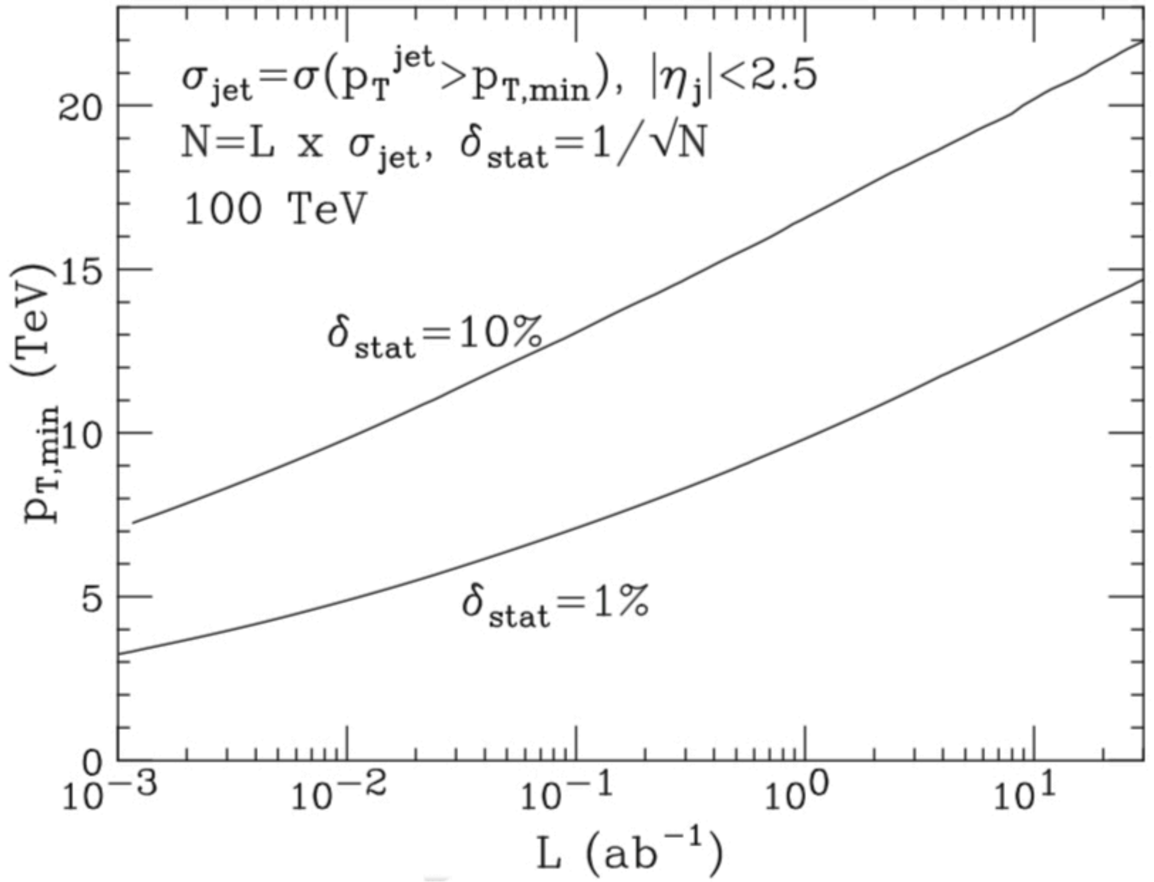
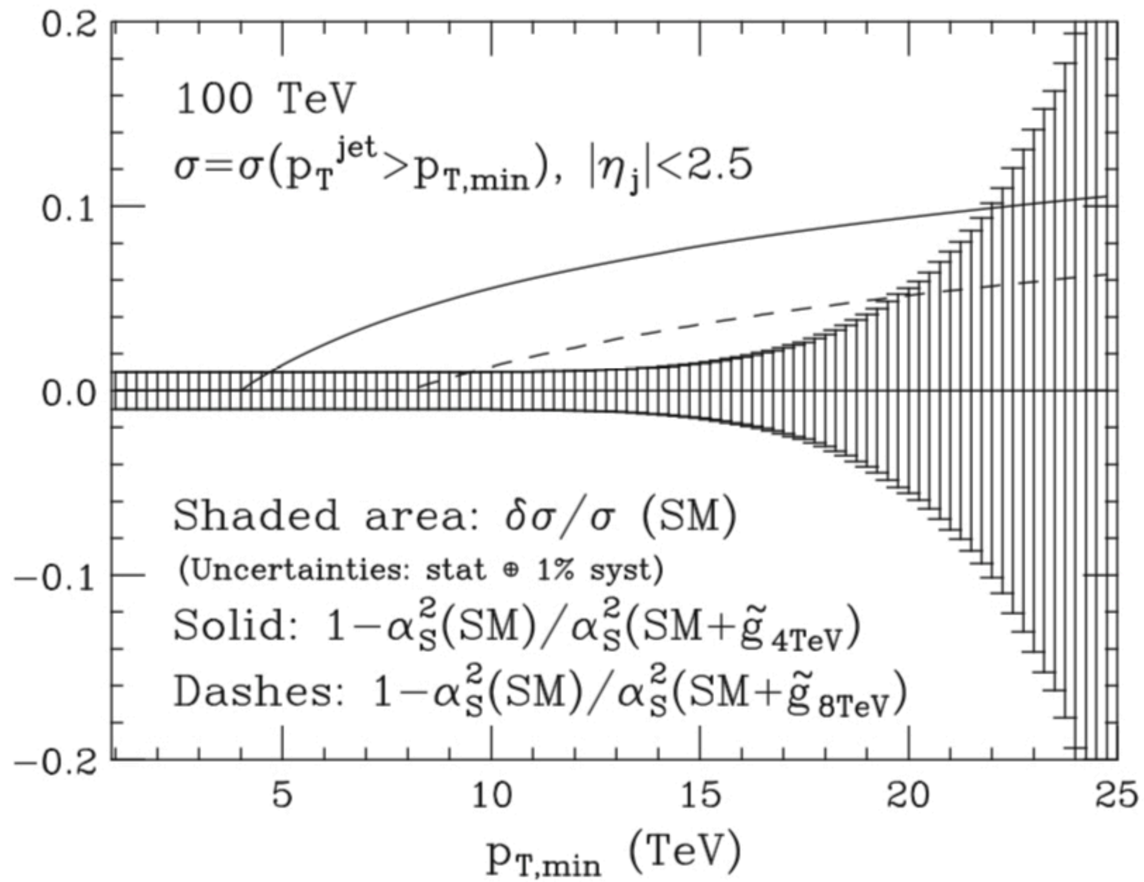
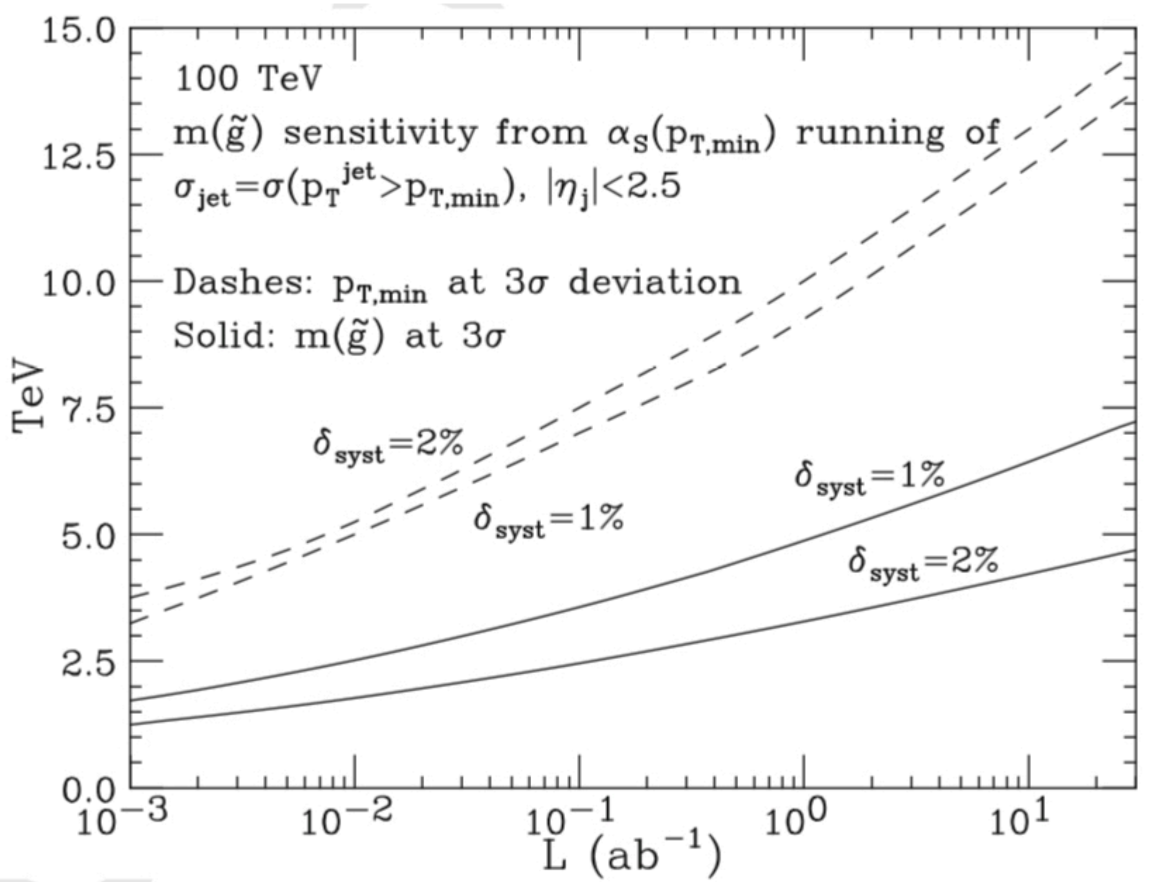


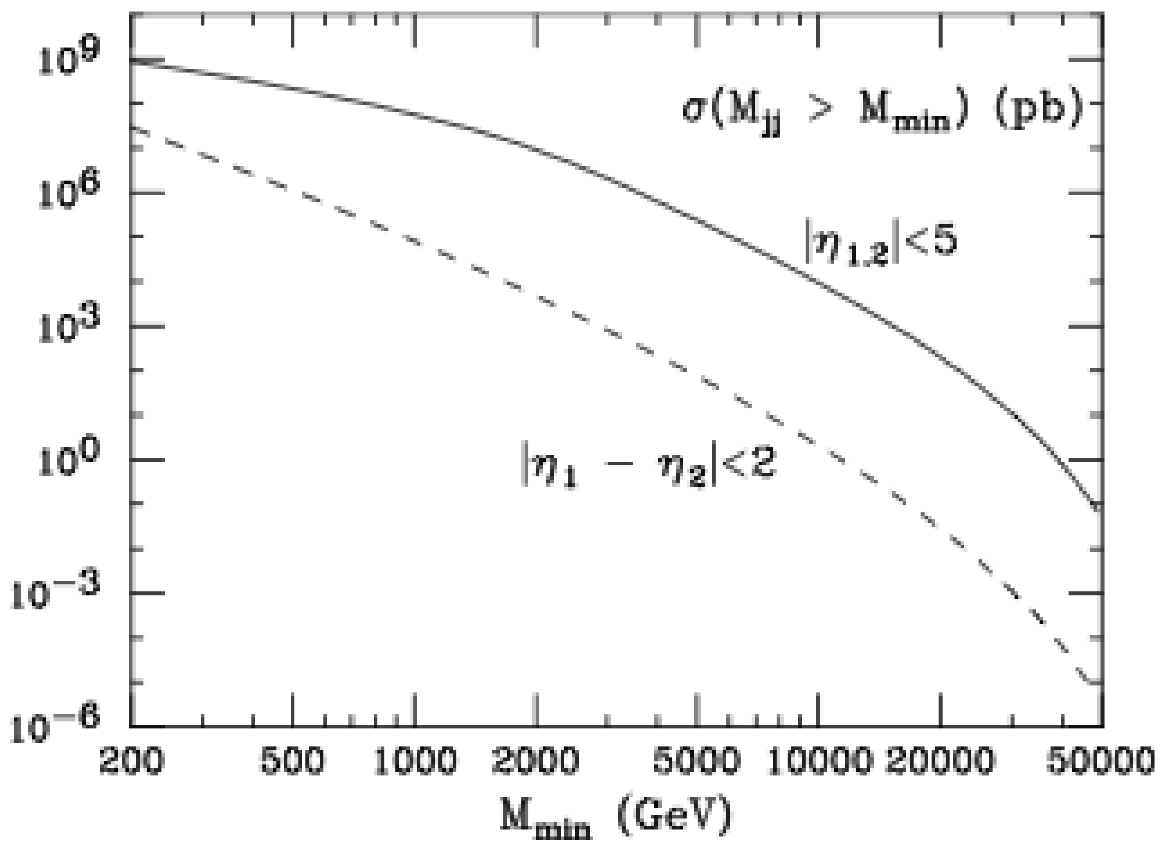


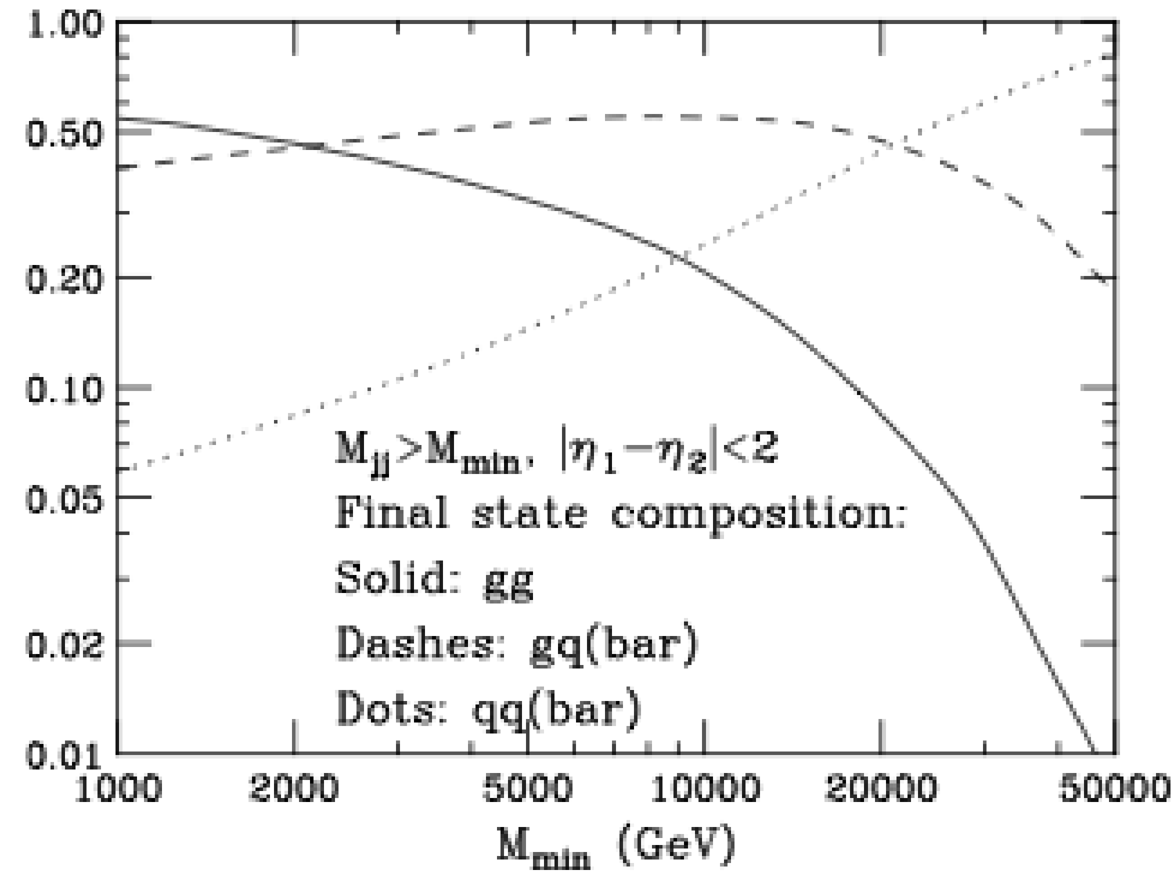
Sensitivity to gluinos from α_S running





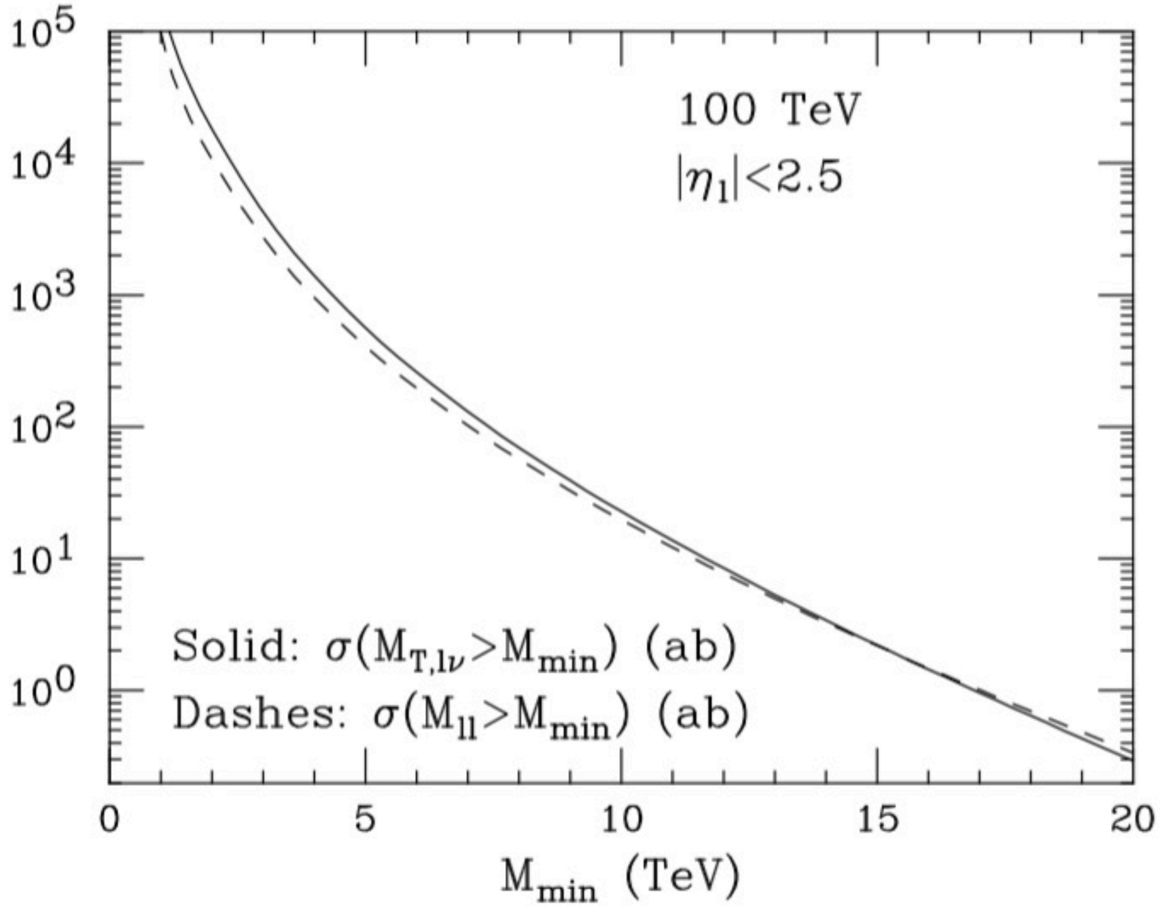
Jet distributions and composition

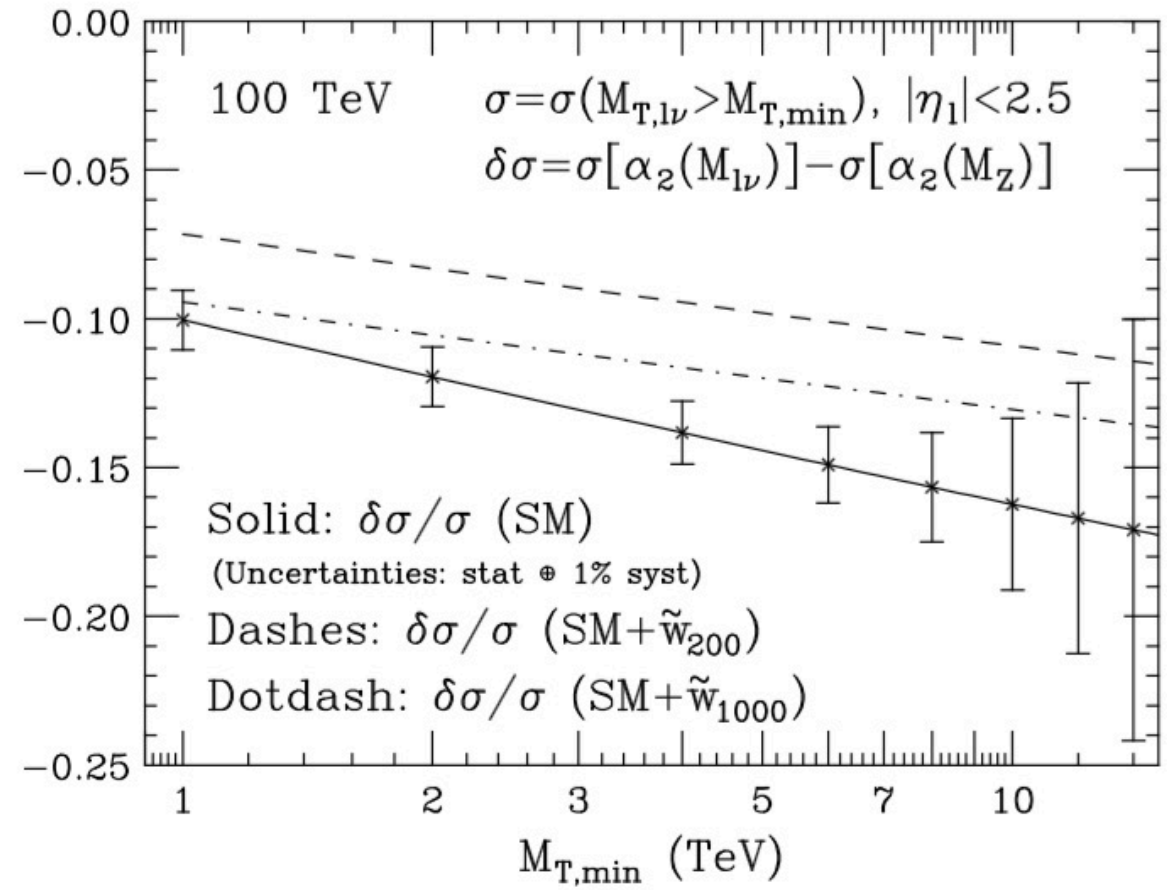




High mass DY

α_W running and sensitivity to new EW particles





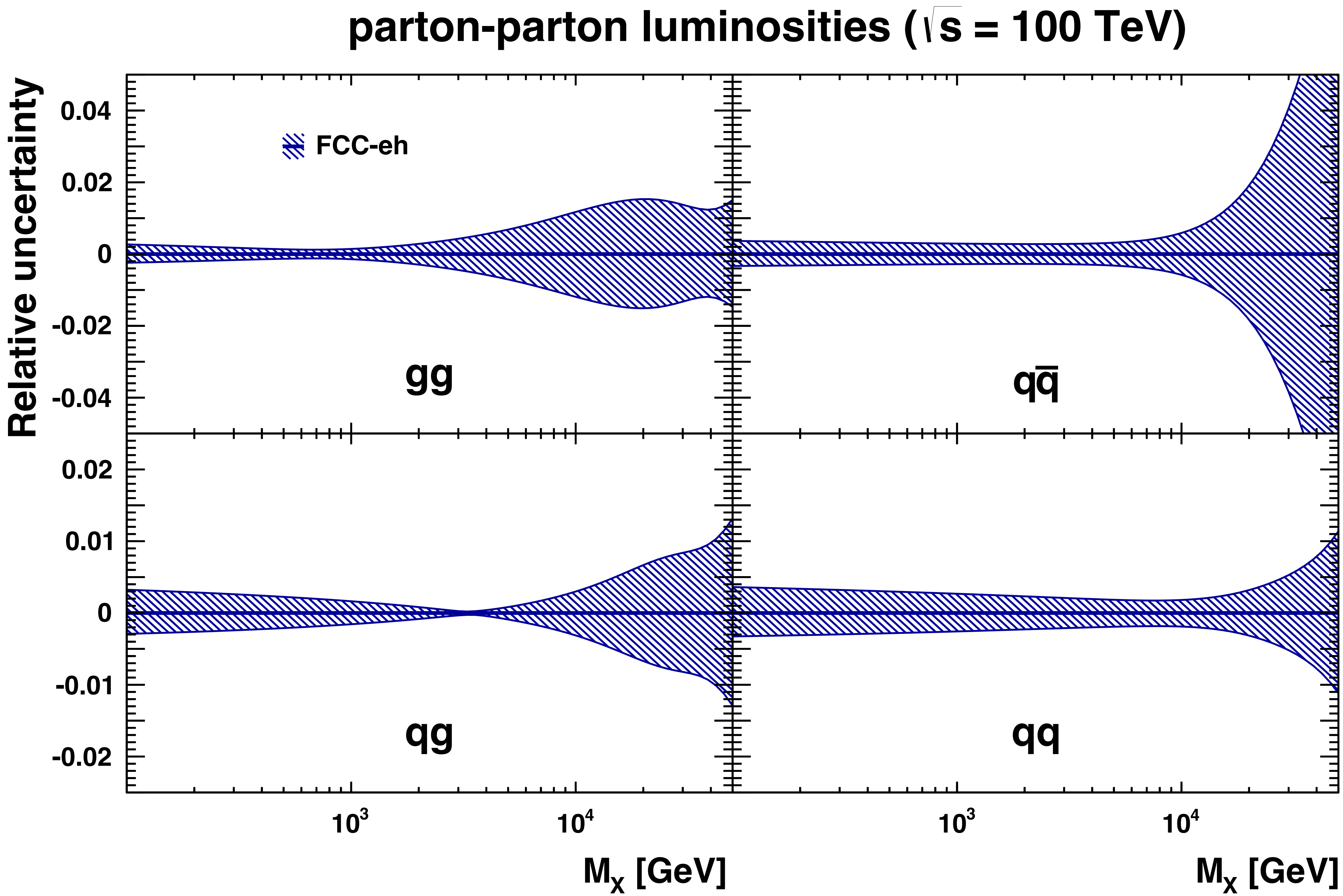
Constraints on Higher-dim op's

$$\hat{W} = -\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \quad , \quad \hat{Y} = -\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

		LEP	ATLAS 8	CMS 8	LHC 13		FCC-hh	FCC-ee
	luminosity	$2\times10^7\,Z$	$19.7\,\text{fb}^{-1}$	$20.3\,\text{fb}^{-1}$	$0.3\,\text{ab}^{-1}$	$3\,\text{ab}^{-1}$	$10\,\text{ab}^{-1}$	$10^{12}\,Z$
NC	W $\times10^4$	$[-19, 3]$	$[-3, 15]$	$[-5, 22]$	±1.5	±0.8	±0.04	±1.2
	Y $\times10^4$	$[-17, 4]$	$[-4, 24]$	$[-7, 41]$	±2.3	±1.2	±0.06	±1.5
CC	W $\times10^4$	—	±3.9		±0.7	±0.45	±0.02	—

$W / 4m_W^2 \;<\; 1 / (100\ \text{TeV})^2$

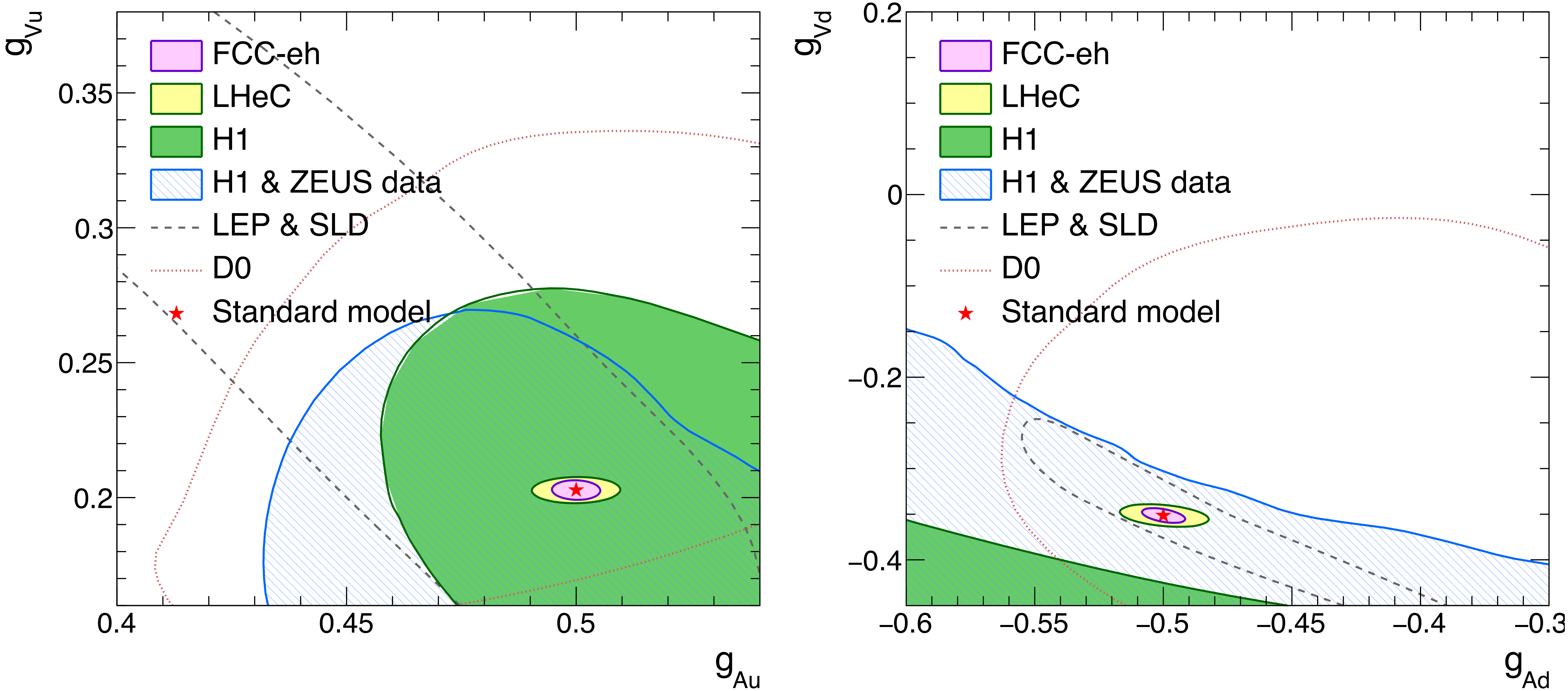
PDF systematics, from FCC-eh



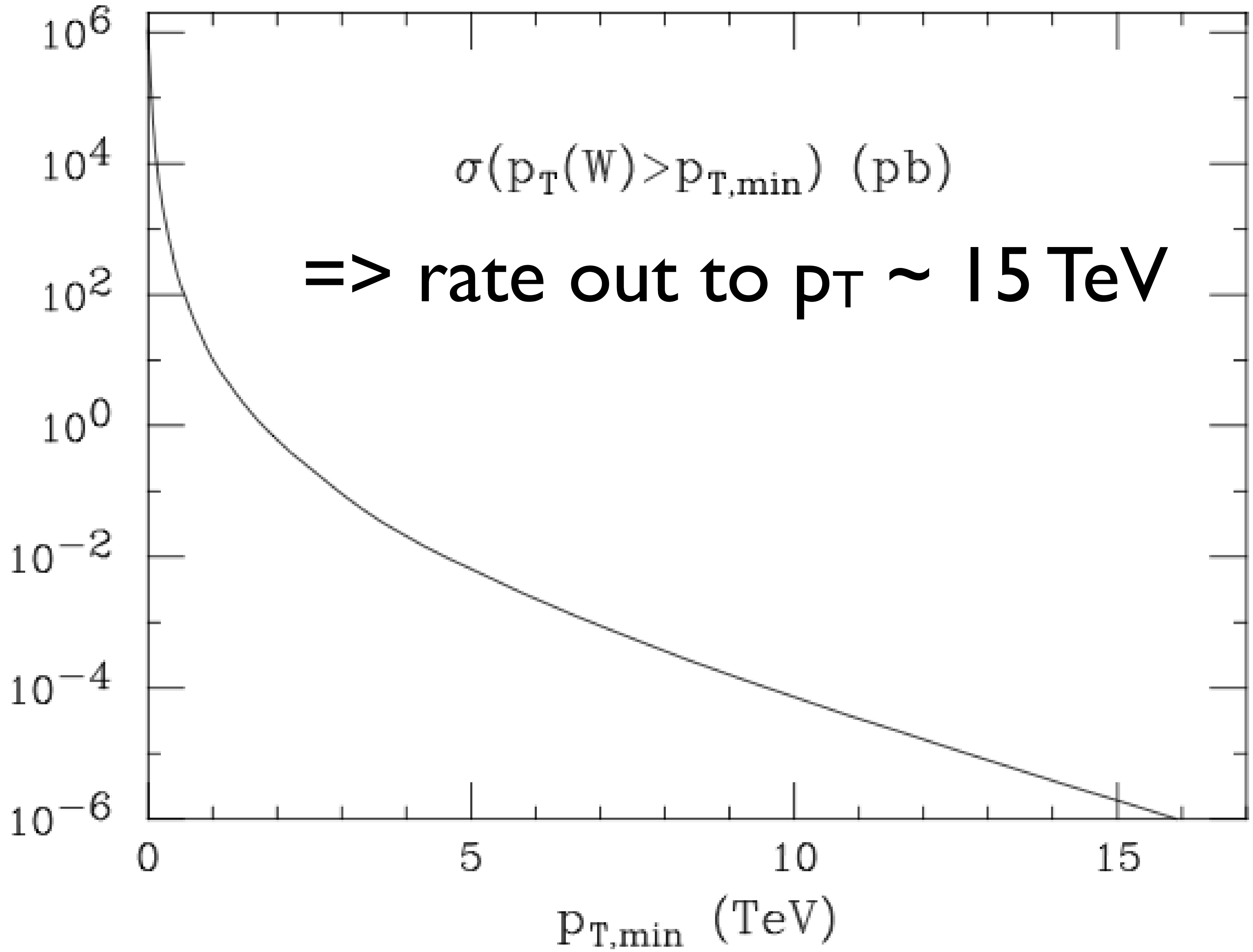
- PDF systematics below 1% for
  - the leading jet-production channel (qq, qg) up to $p_T \sim 20$ TeV
  - DY (qqbar) up to the the range of statistics (M~15 TeV), syst below 5% up to the mass discovery reach, around 40 TeV

u/d EW couplings from NC/CC DIS at FCC-eh

DIS scattering doesn't just provide improved PDFs, it also allows to separate $u_{L,R}$ and $d_{L,R}$ weak couplings

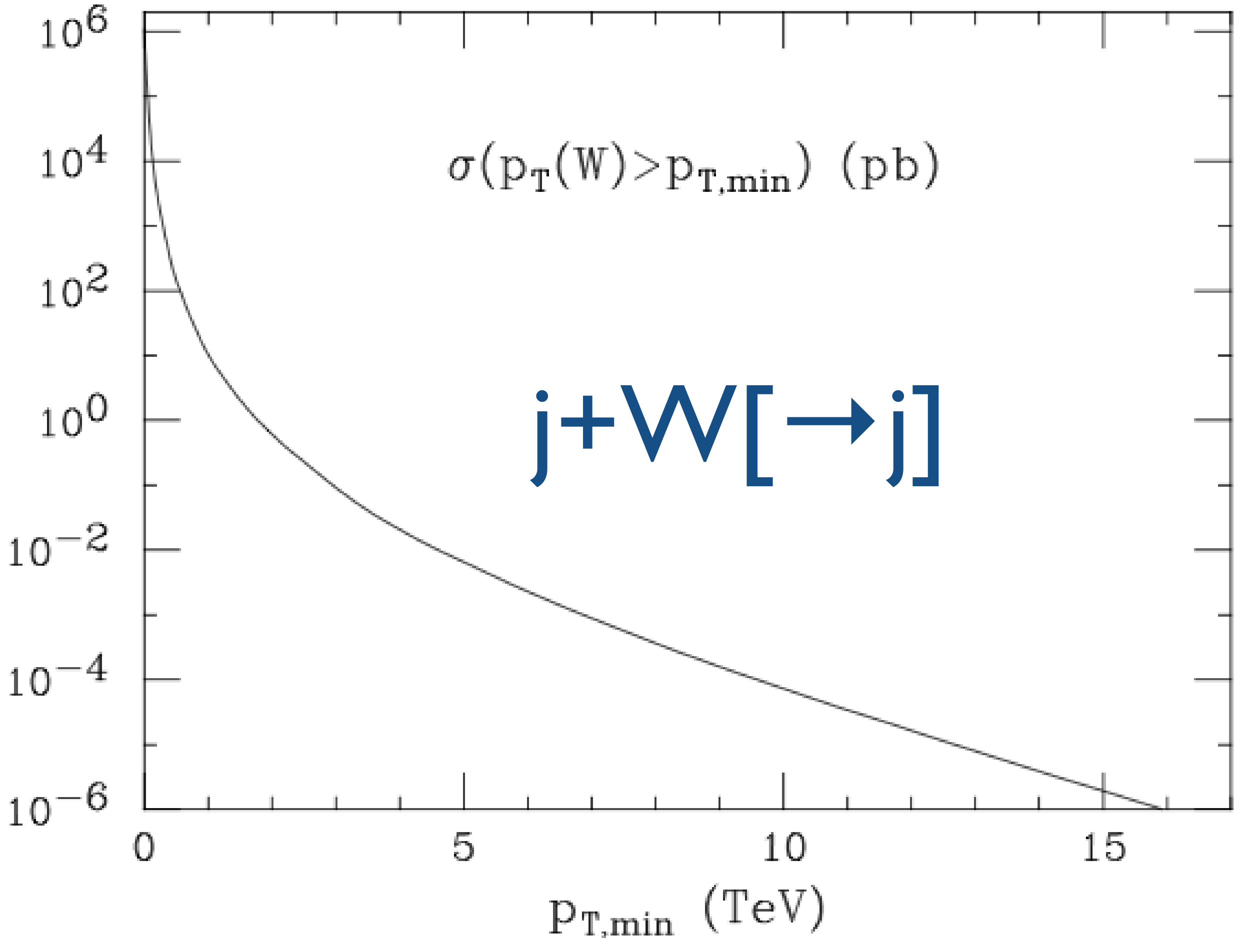


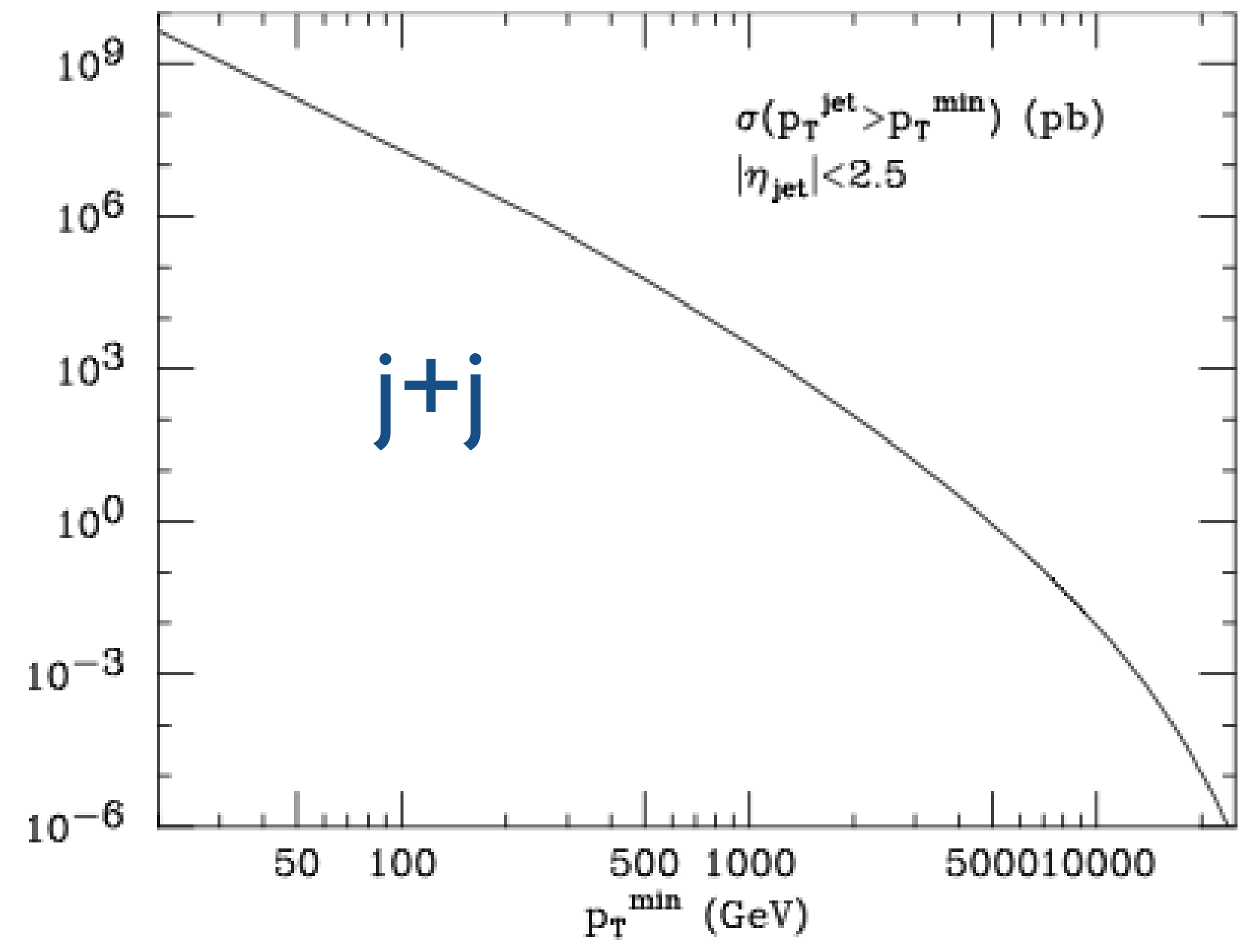
W production at large pt



Possible implications:

- $W \to \ell\nu$ source of MET in the multi-TeV region
- Can use hadronic W and/or Z decays to control MET systematics? (larger statistics than leptonic channels at high MET)



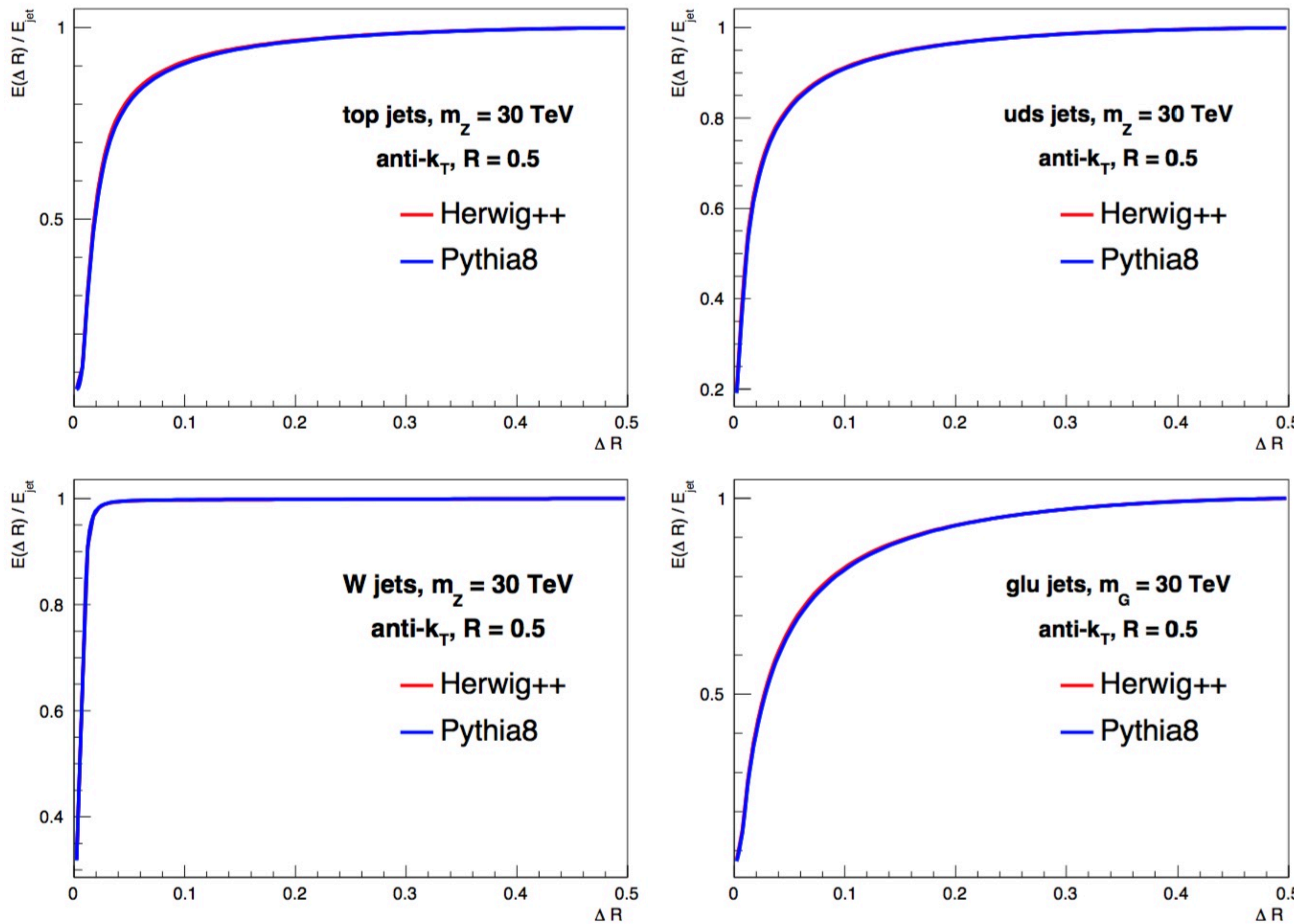


W[→j]/j ~ 10^{-2}: to which extend will it be possible to use systematically hadronic W/Z decays?

Jet structure at multi-TeV energies

* see also
Sung Hak Lim talk

Jets' energy shape: E(r<R) / E_{jet}
(⇒ calorimeter granularity, tracker)

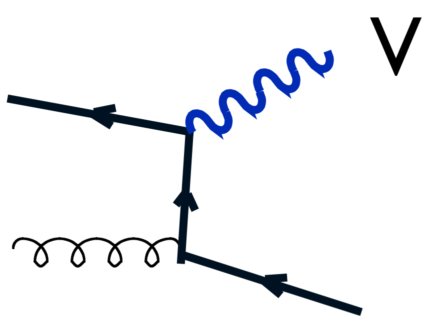


A 15 TeV W[→j] has 95% of its energy within R<0.02. A QCD jet has only 50% of its energy in such a cone

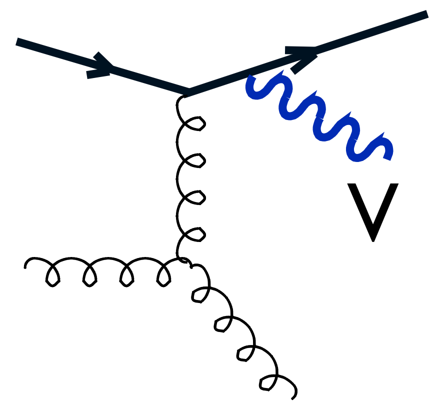
Fig. 116: Average energy fraction contained within and angular scale ΔR of jets produced from 30 TeV resonance decays to tops, light QCD quarks, Ws, and gluons.

Production of gauge bosons in high-energy final states ($\sqrt{s} \gg M_V$)

$O(\alpha_S)$



⇒ $\sqrt{s} \approx p_T^V \gg M_V$



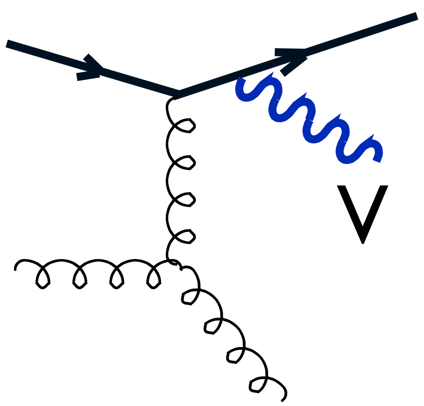
$O(\alpha_S^2)$, but enhanced by t-channel g exchange, and by $\log(p_T^{jet}/M_W)$

⇒ **could be larger than $O(\alpha_S)$**
⇒ **no strong ordering between p_T^V and M_V**

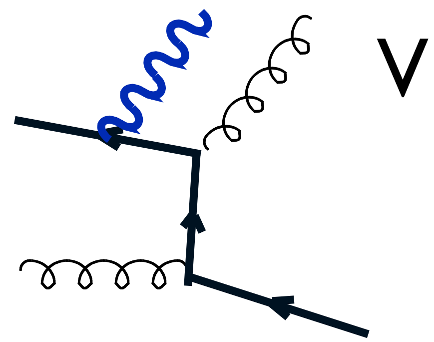
- Need to include $O(\alpha_S^2)$ in order to capture all sources of V production.
- This requires, in principle, the complete $O(\alpha_S^2)$ calculation, inclusive of virtual corrections to $O(\alpha_S)$.
- But the contribution from the soft-jet region to the enhanced EW logs is marginal, so one can define observables which are insensitive to the jet Sudakov region

In practice, I will consider p_T>30 GeV for both jets, and explore the TeV region for E_T(leading jet)

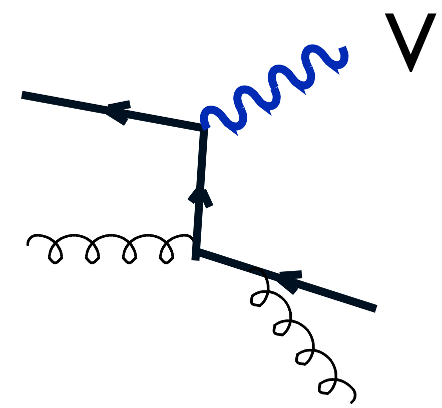
Study V emission rate in dijet events at very large $E_T^{(\text{leading jet})}$



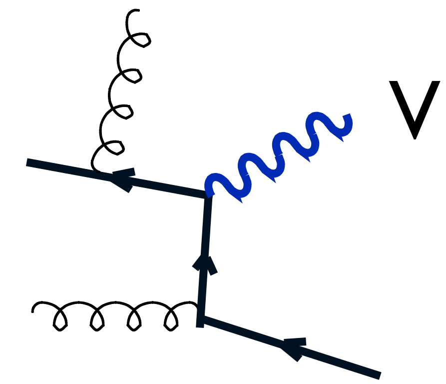
Large EW logs,
V correlated to jet



Large EW logs,
V not correlated
to jet



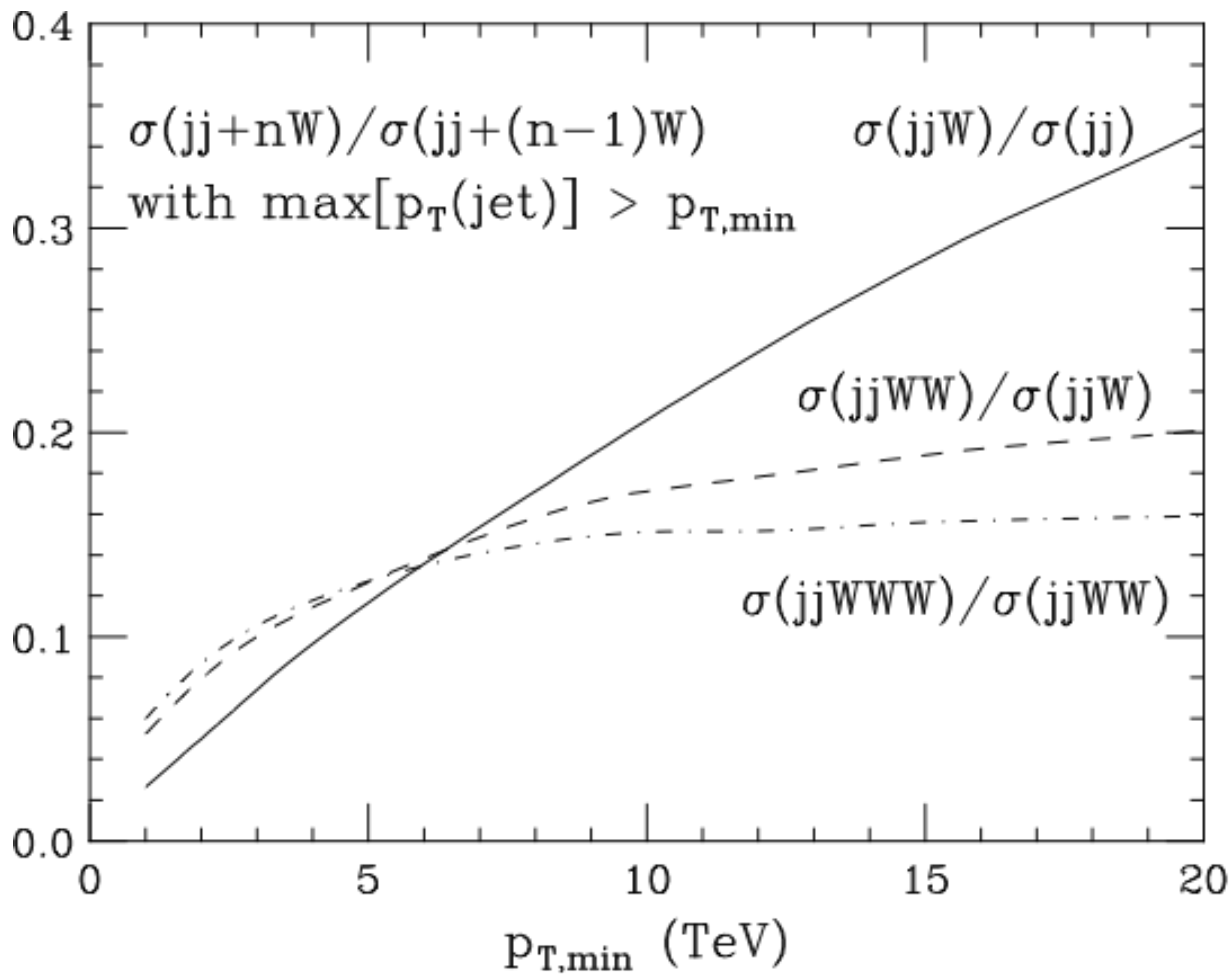
Radiative
correction to V+jet,
no EW log



Radiative
correction to V+jet,
no EW log

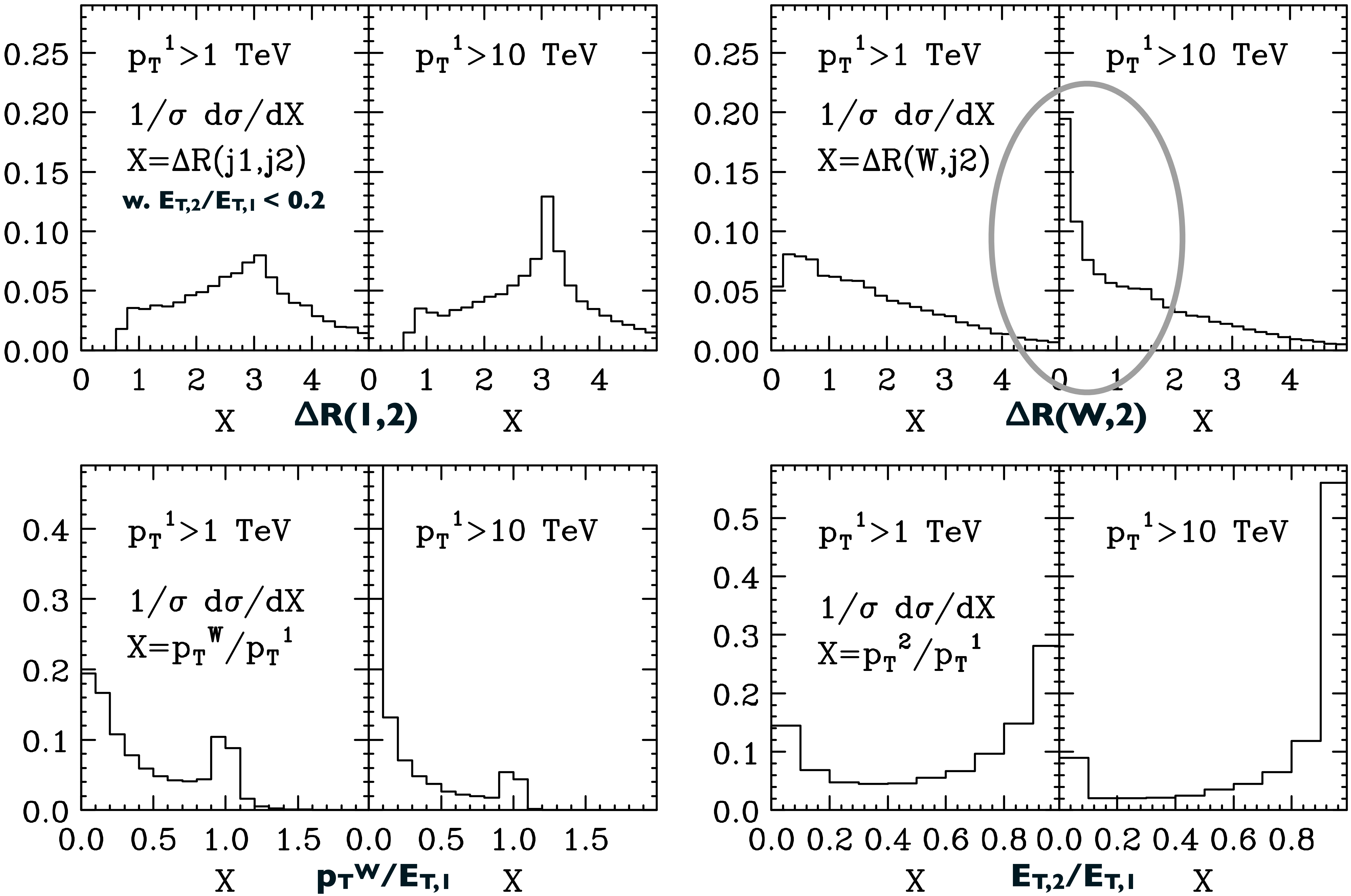
Study σ(jet jet + V) / σ(jet jet) vs $E_T^{(\text{leading jet})}$

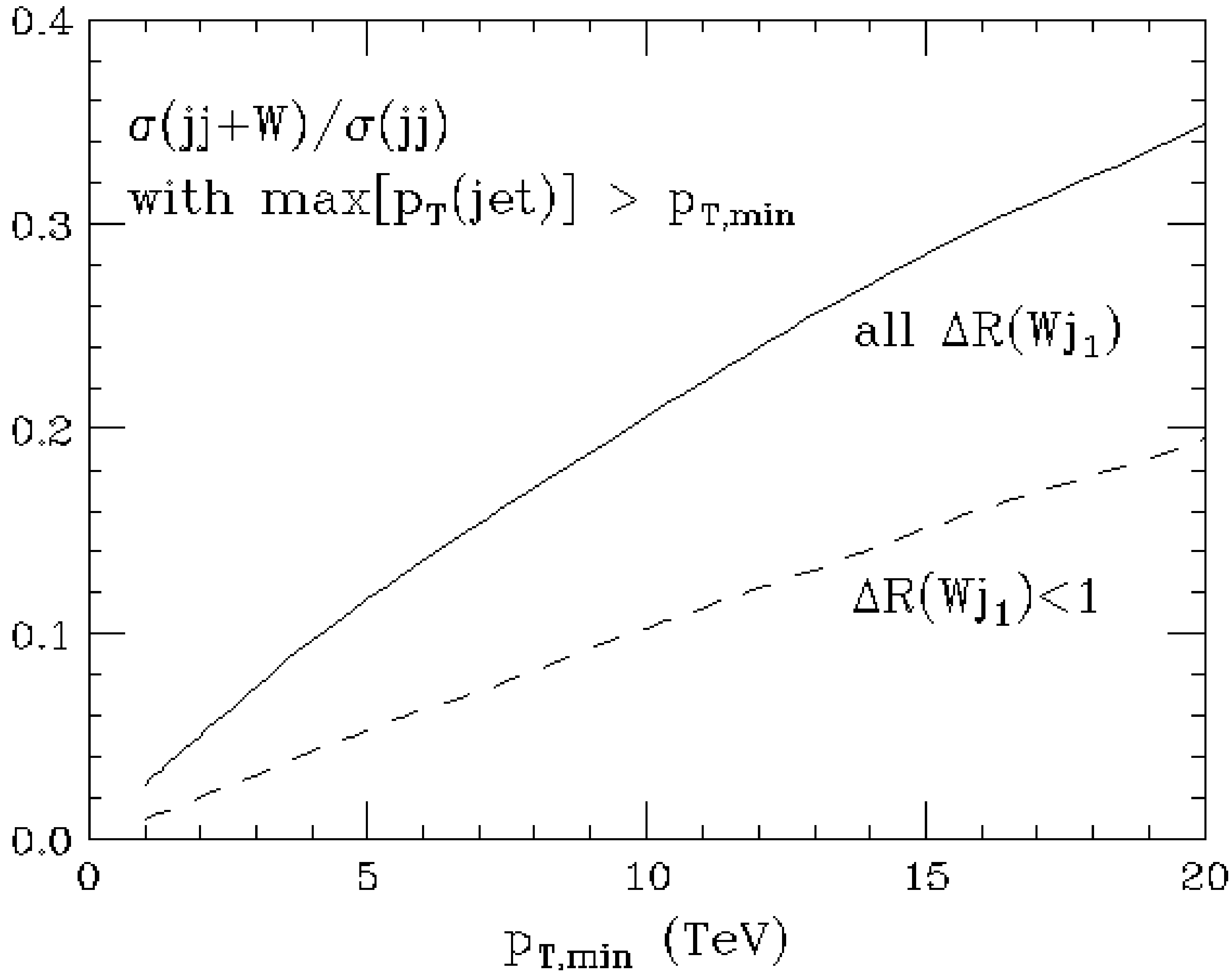
W emission rates from jets



W emission distributions

which fraction of Ws can be associated to radiation off the jet, vs ISR or ISR/FSR interference?

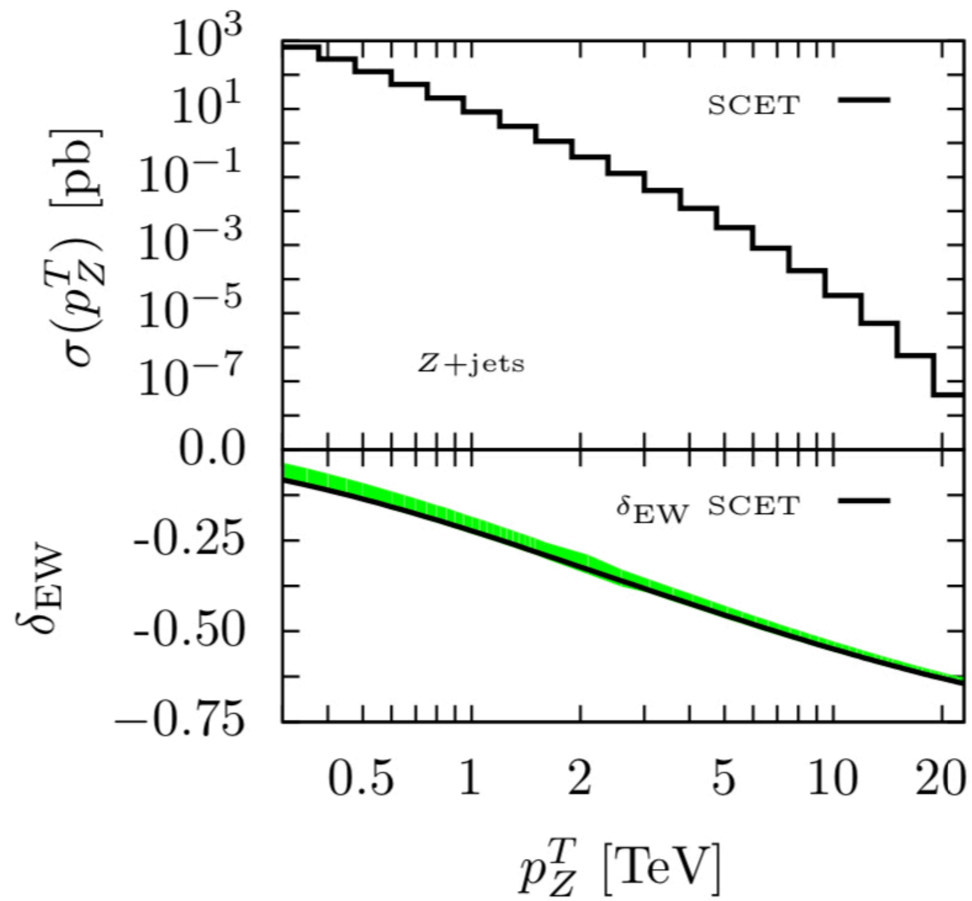


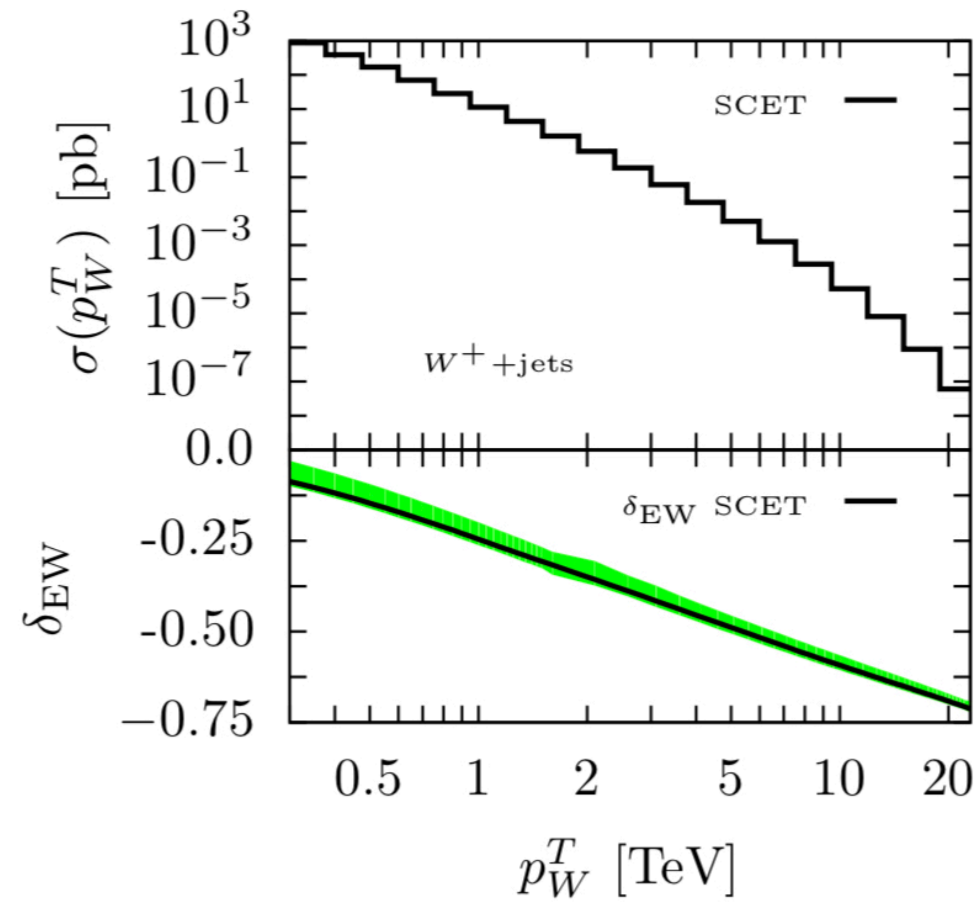


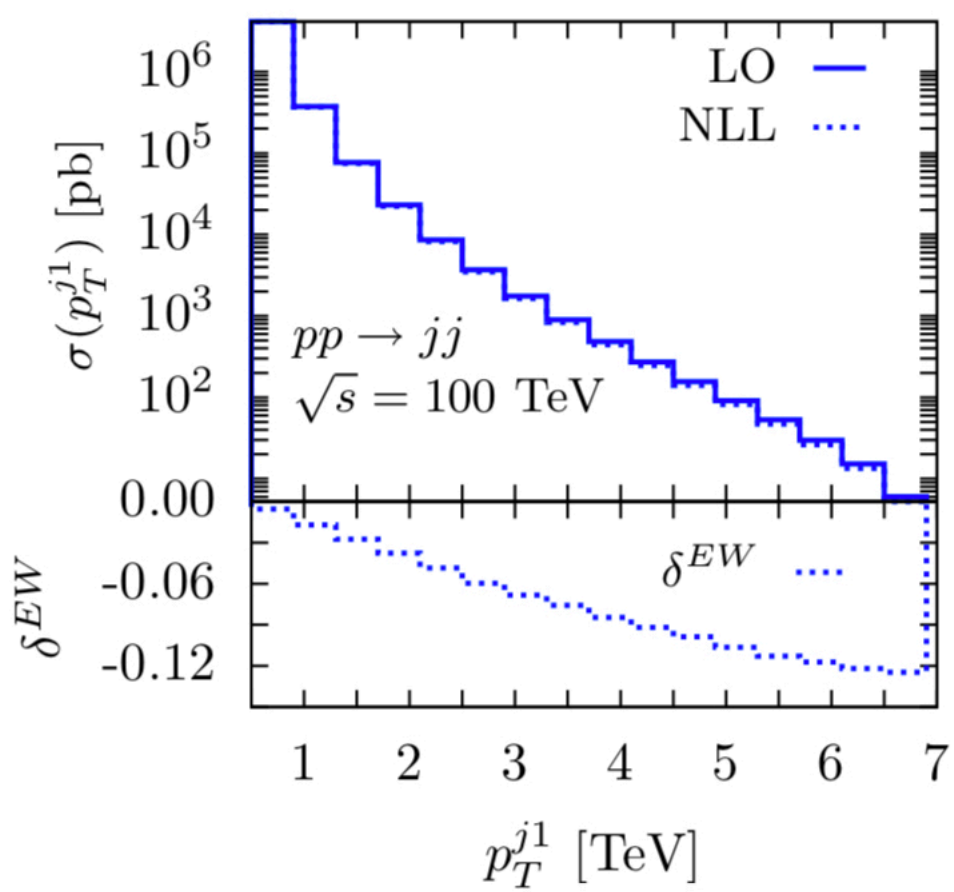
Possible implications:

- 10-20% probability of q→qW ⇒ may need b-tagging to separate top jet above 1- TeV from ordinary light-q jet?

EW corrections to QCD observables

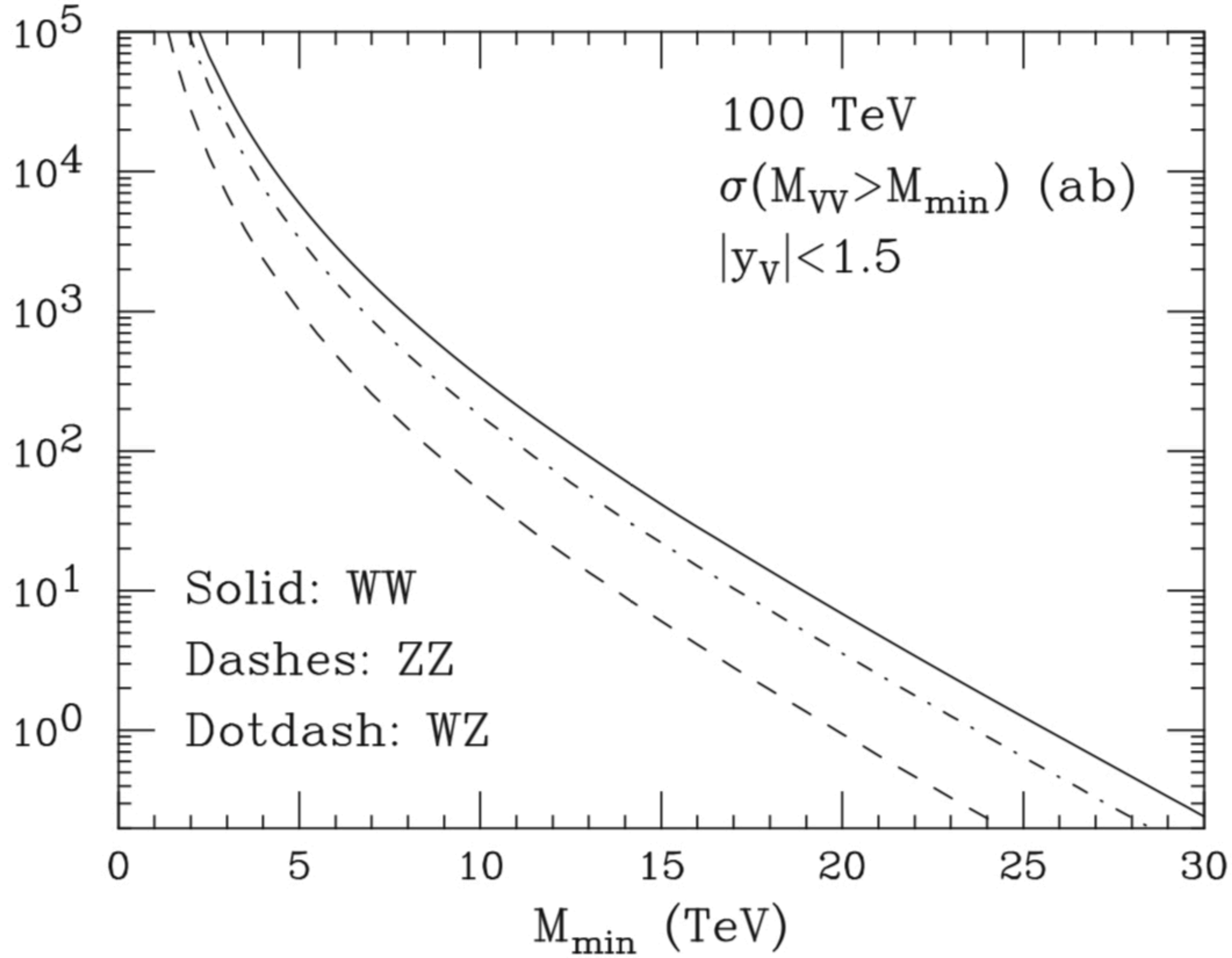


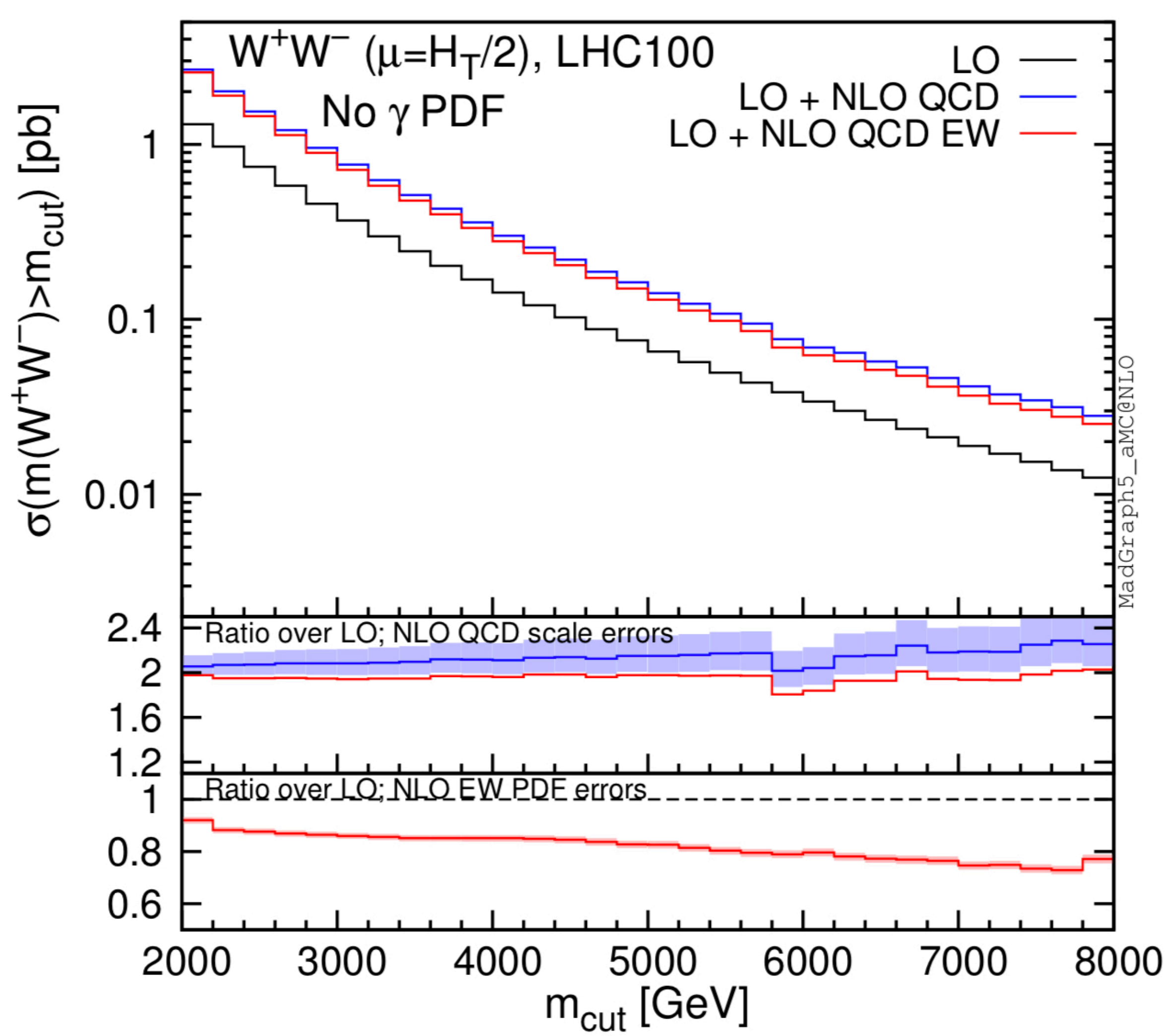




EW effects become large at large Q^2, and must be included in any application to precision physics

VV production





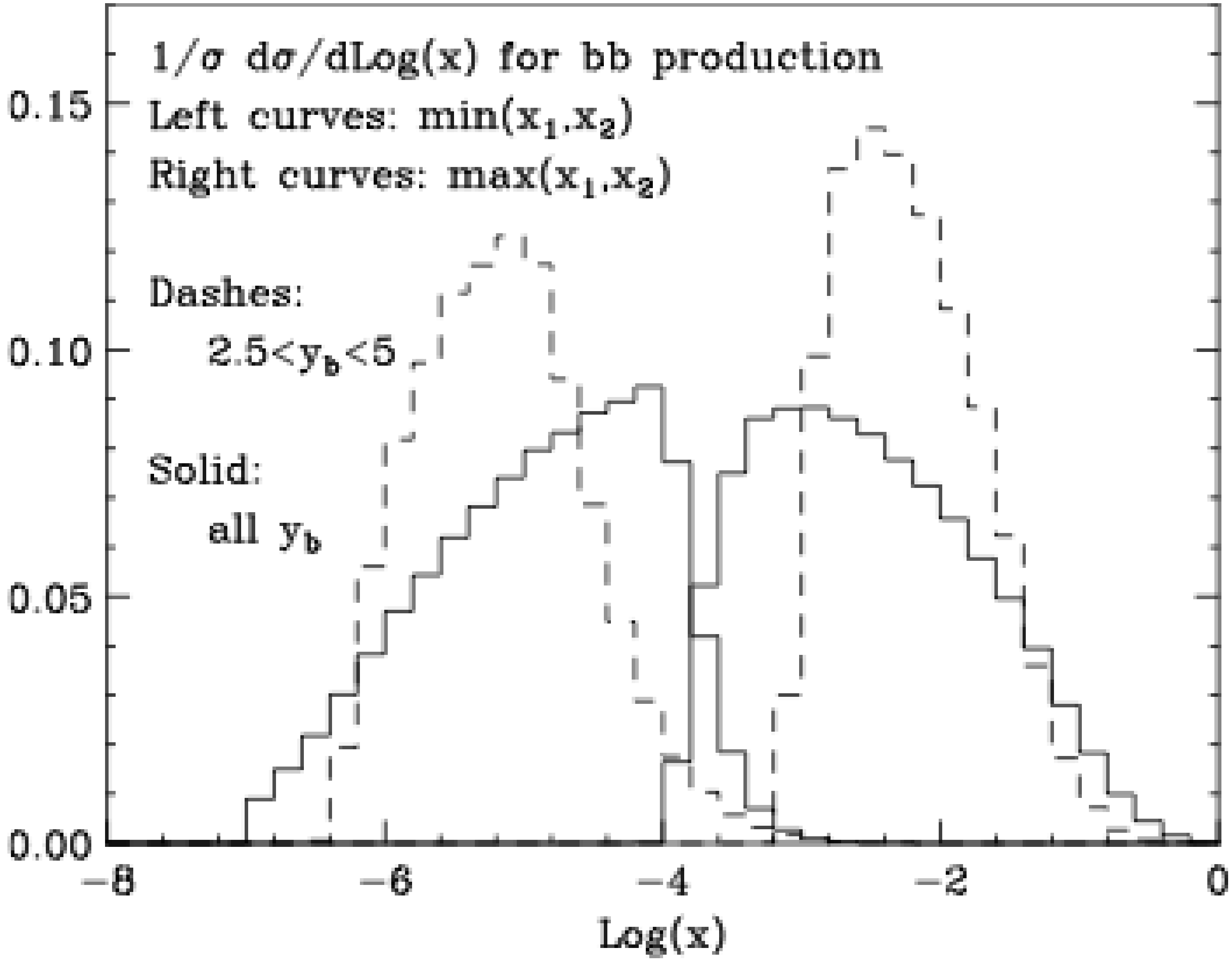
Heavy quark production: c & b

PDF sets	$\sigma(c\bar{c})^{\rm NLO}$ [mb]	$\sigma(c\bar{c})^{\rm NNLO}$ [mb]	$\sigma(b\bar{b})^{\rm NLO}$ [mb]	$\sigma(b\bar{b})^{\rm NNLO}$ [mb]
ABM11 [396]	29.5 ± 2.7	36.6 ± 2.6 (54.9 ± 3.8) *	3.57 ± 0.13	3.06 ± 0.11 (4.52 ± 0.18)
ABM12 [20] [46]	17.3 ± 2.0	33.2 ± 2.6	2.36 ± 0.10	2.97 ± 0.12
CJ15 [22] [47]	$18.4\,^{+\,5.3}_{-\,2.5}$	– $(40.3\,^{+\,10.3}_{-\,4.6})$	$2.67\,^{+\,0.55}_{-\,0.26}$	– $(3.42\,^{+\,0.69}_{-\,0.31})$
CT14 [18] [48]	$24.7\,^{+\,1315.5}_{-\,3.1}$	$31.8\,^{+\,624.3}_{-\,3.0}$ $(47.9\,^{+\,1981.2}_{-\,5.2})$	$3.06\,^{+\,5.35}_{-\,0.25}$	$3.12\,^{+\,3.39}_{-\,0.21}$ $(3.91\,^{+\,6.91}_{-\,0.30})$
HERAPDF2.0 [21] [49]	$19.0\,^{+\,3.8}_{-\,4.4}$	$3.2\,^{+\,10.1}_{-\,18.2}$ $(41.5\,^{+\,5.2}_{-\,5.9})$	$3.14\,^{+\,0.10}_{-\,0.13}$	$2.70\,^{+\,0.21}_{-\,0.22}$ $(4.01\,^{+\,0.13}_{-\,0.16})$
JR14 (dyn) [23]	33.6 ± 0.5	32.7 ± 0.5 (58.1 ± 1.0)	3.17 ± 0.04	3.08 ± 0.04 (3.98 ± 0.06)
MMHT14 [19] [50]	$140.0\,^{+\,187.0}_{-\,104.2}$	– $\sigma<0$ $(213.9\,^{+\,271.9}_{-\,149.4})$	$4.11\,^{+\,1.39}_{-\,0.90}$	$2.37\,^{+\,0.98}_{-\,0.90}$ $(5.28\,^{+\,1.77}_{-\,1.14})$
NNPDF3.0 [17]	40.5 ± 62.2	190.3 ± 547.7 (67.9 ± 84.3)	2.99 ± 0.99	4.46 ± 4.87 (3.82 ± 1.23)

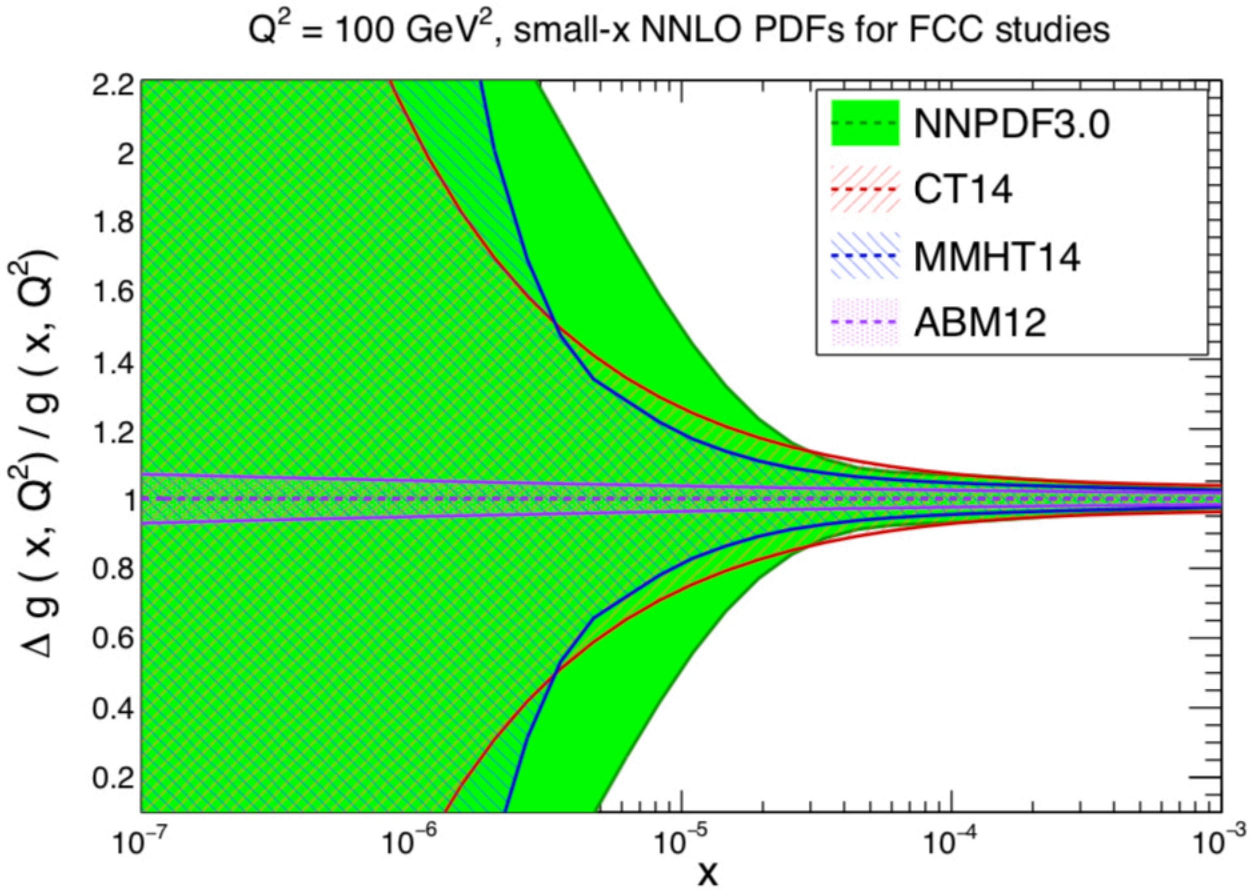
* #s in () are NNLO w. NLO PDF

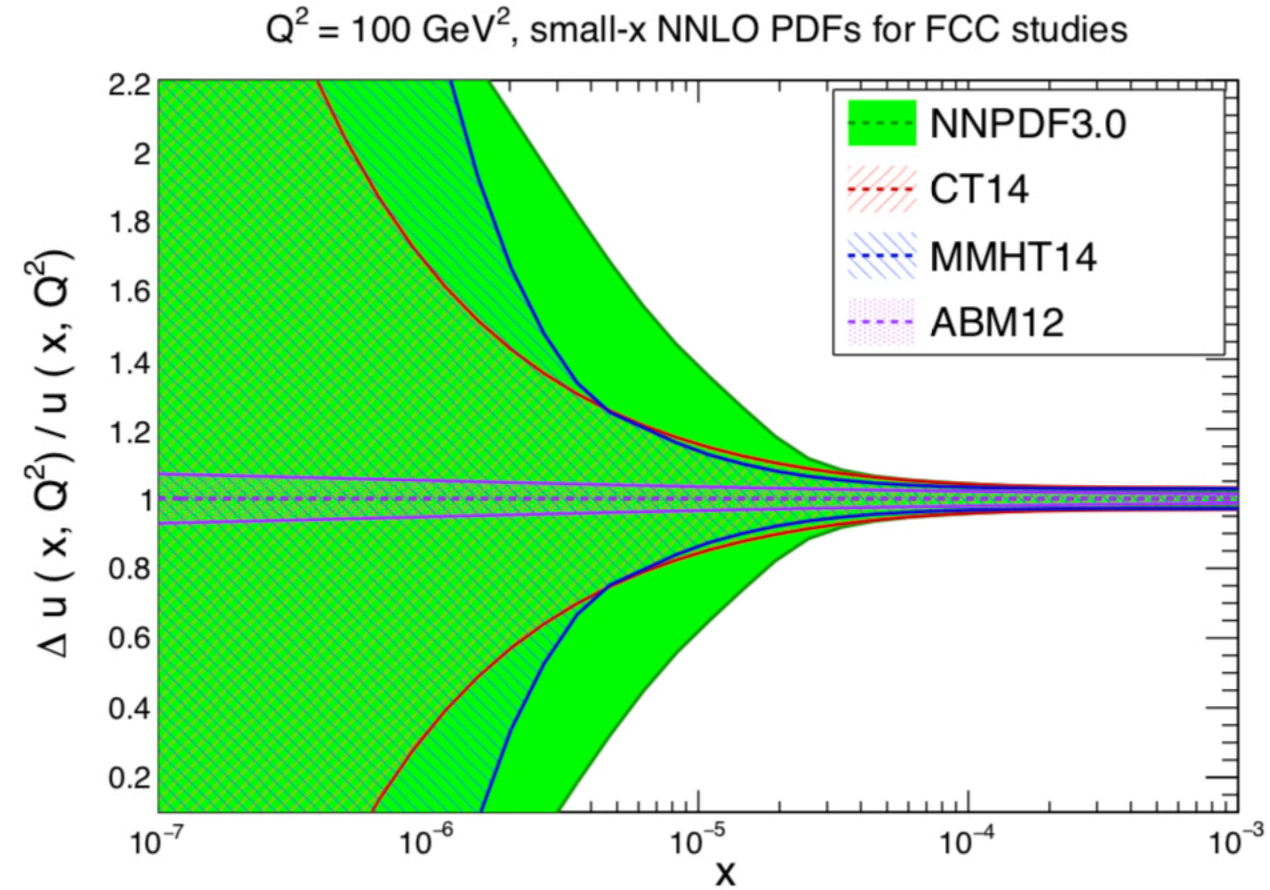
underscores issues with PDF parameterizations and small-x extrapolations

Bottom quark production: small-x reach



PDF luminosity uncertainties, today





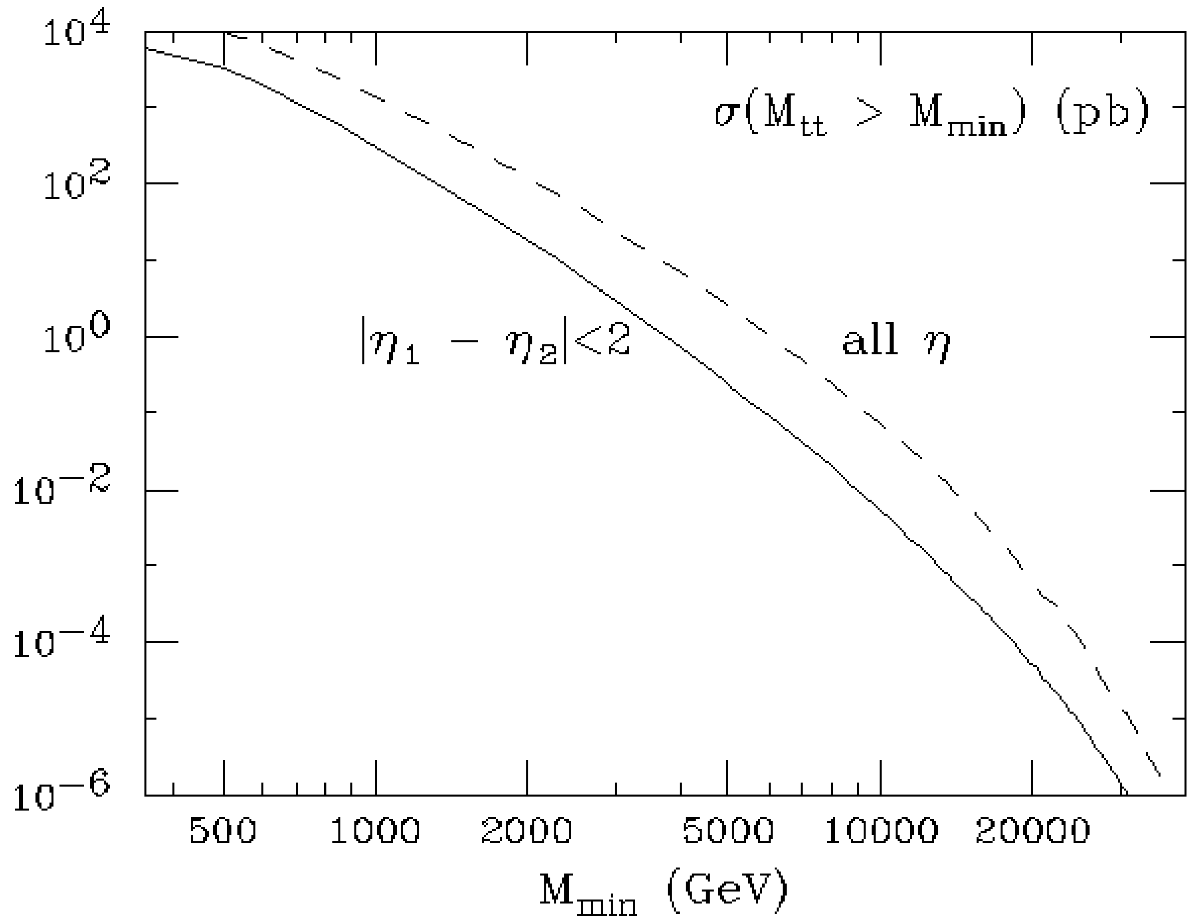
Top quark production in pp@100 TeV

PDF	σ(nb)	δ_{scale}(nb)	(%)	δ_{PDF}(nb)	(%)
CT14	34.692	$+1.000$ -1.649	$(+2.9\%)$ (-4.7%)	$+0.660$ -0.650	$(+1.9\%)$ (-1.9%)
NNPDF3.0	34.810	$+1.002$ -1.653	$(+2.9\%)$ (-4.7%)	$+1.092$ -1.311	$(+3.1\%)$ (-3.8%)
PDF4LHC15	34.733	$+1.001$ -1.650	$(+2.9\%)$ (-4.7%)	± 0.590	$(\pm 1.7\%)$

σ_{tot}(100 TeV) ~ 35 x σ_{tot}(14 TeV)

- ⇒ about 10^{12} top quarks produced in 20 ab^{-1}
  - rare and forbidden top decays
  - 10^{12} fully inclusive W decays, triggerable by "the other W"
    - rare and forbidden W decays
    - 3 10^{11} W→charm decays
    - 10^{11} W→tau decays
  - 10^{12} fully charge-tagged b hadrons

Inclusive top quark production



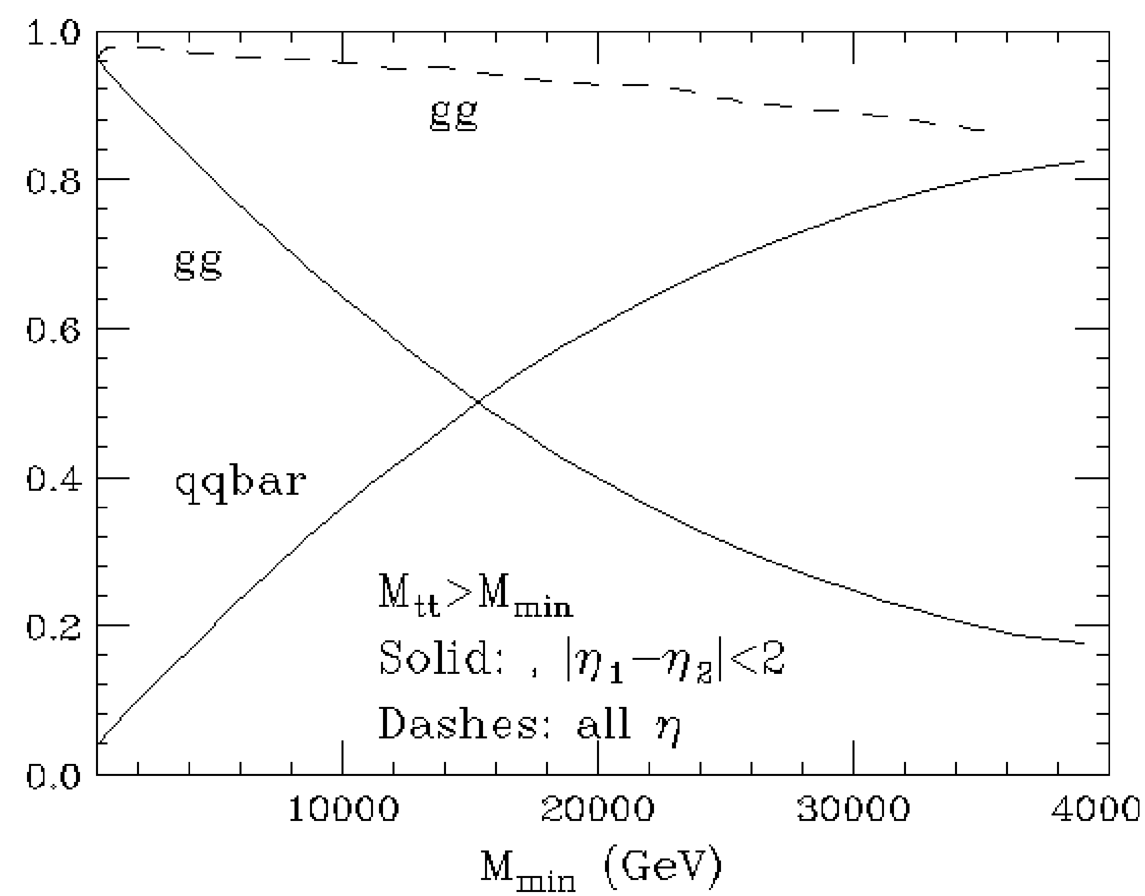
Ex: integrated rates as a function of t-tbar invariant mass for centrally (inclusive) produced tops

Statistics out to over 30 TeV with 10ab^{-1}
Inclusive rate ~ 10 times larger at highest mass

Ex: gg initial state content for central (vs inclusive) t-tbar pairs, vs M(tt)

In central production, dominated by gg up to ~ 15 TeV. Still 20% gg at the kinematic edge of ~ 30 TeV

For inclusive prodution, >90% gg!



tt threshold in ee

TH state of the art: NNNLO QCD + NNLO SM + LL ISR + NNNLO Yukawa

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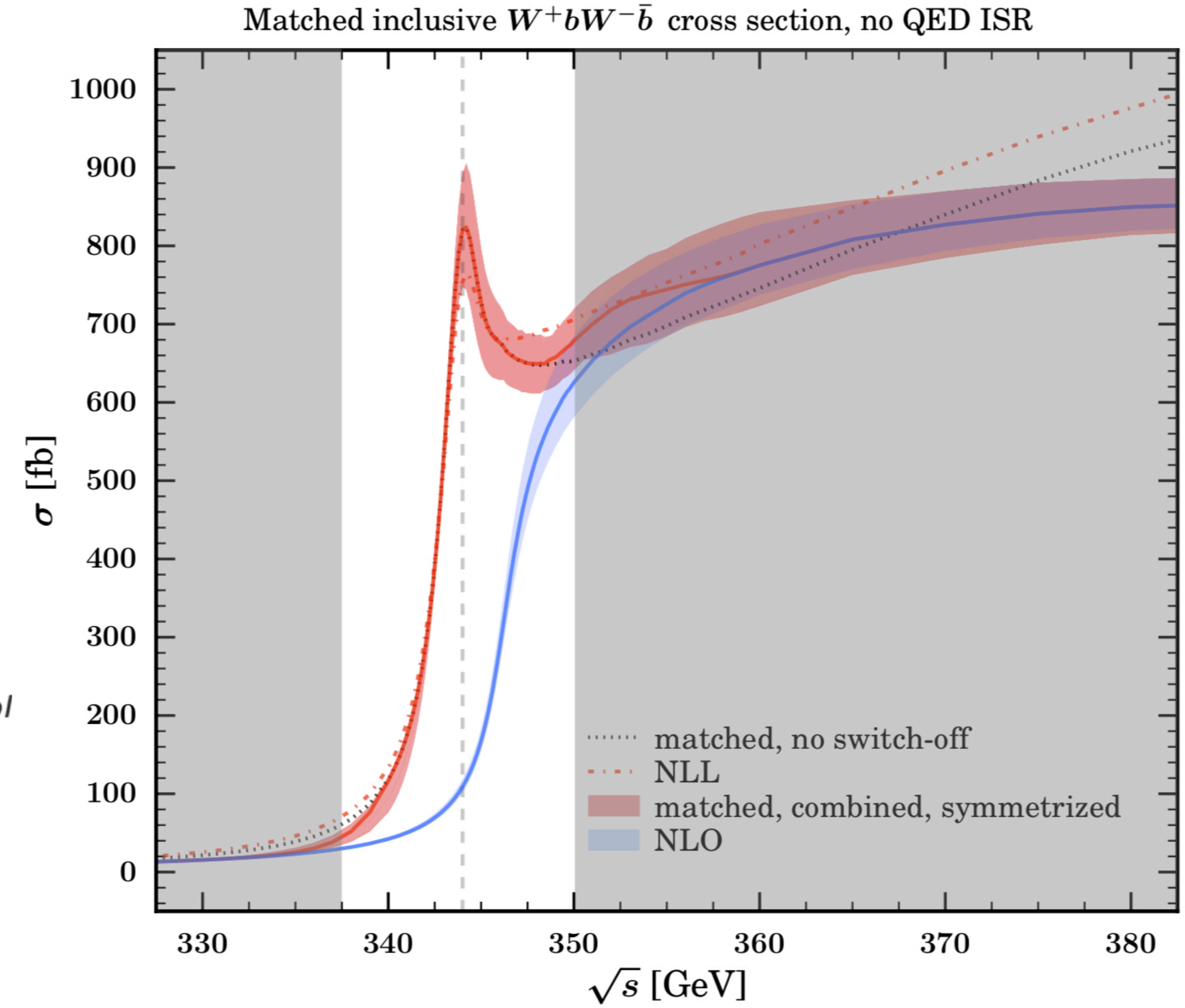

[Bach, Chokoufé Nejad, Hoang, Kilian, Reuter, Stahlhofen, Teubner, Weiss 2017]

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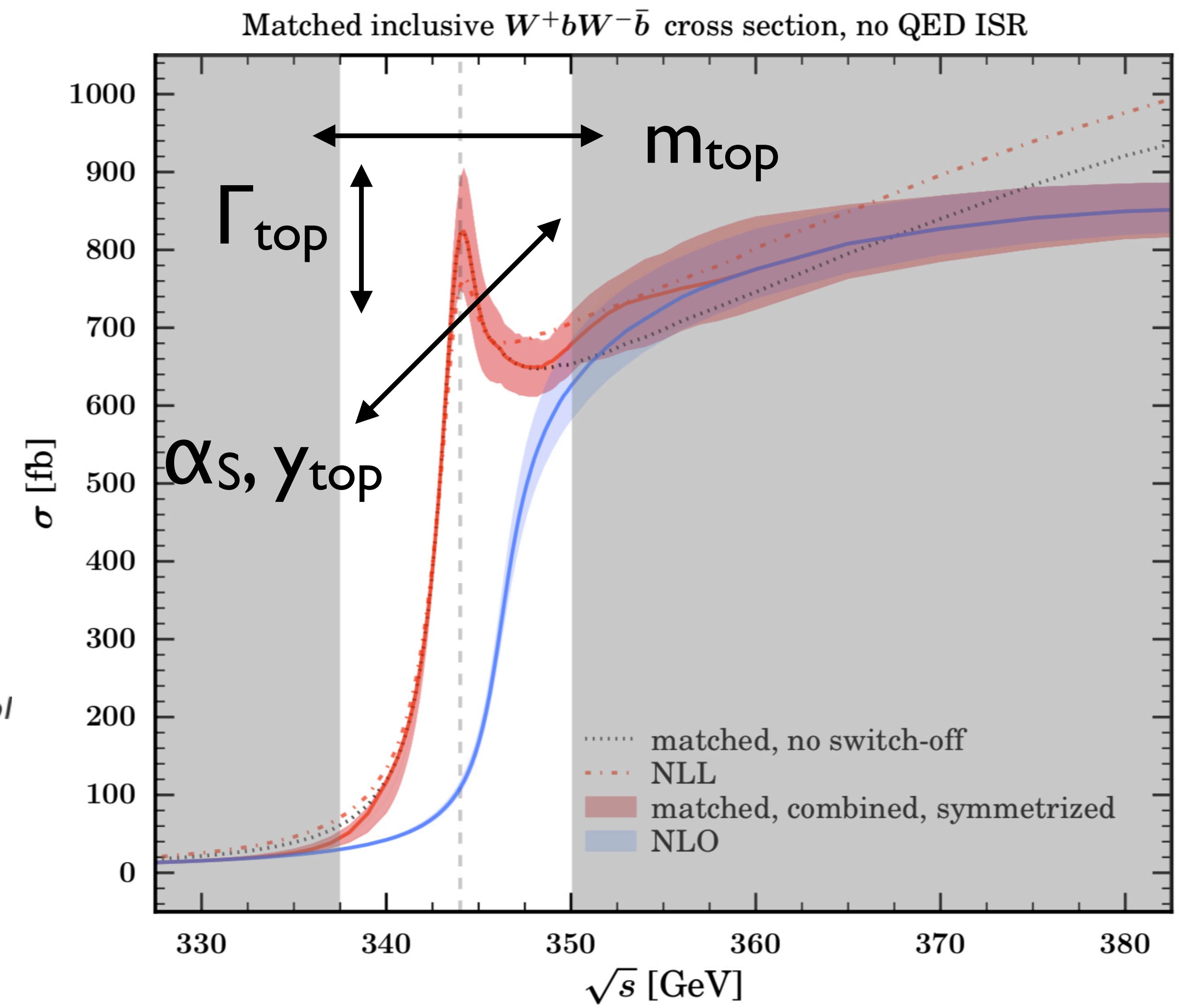

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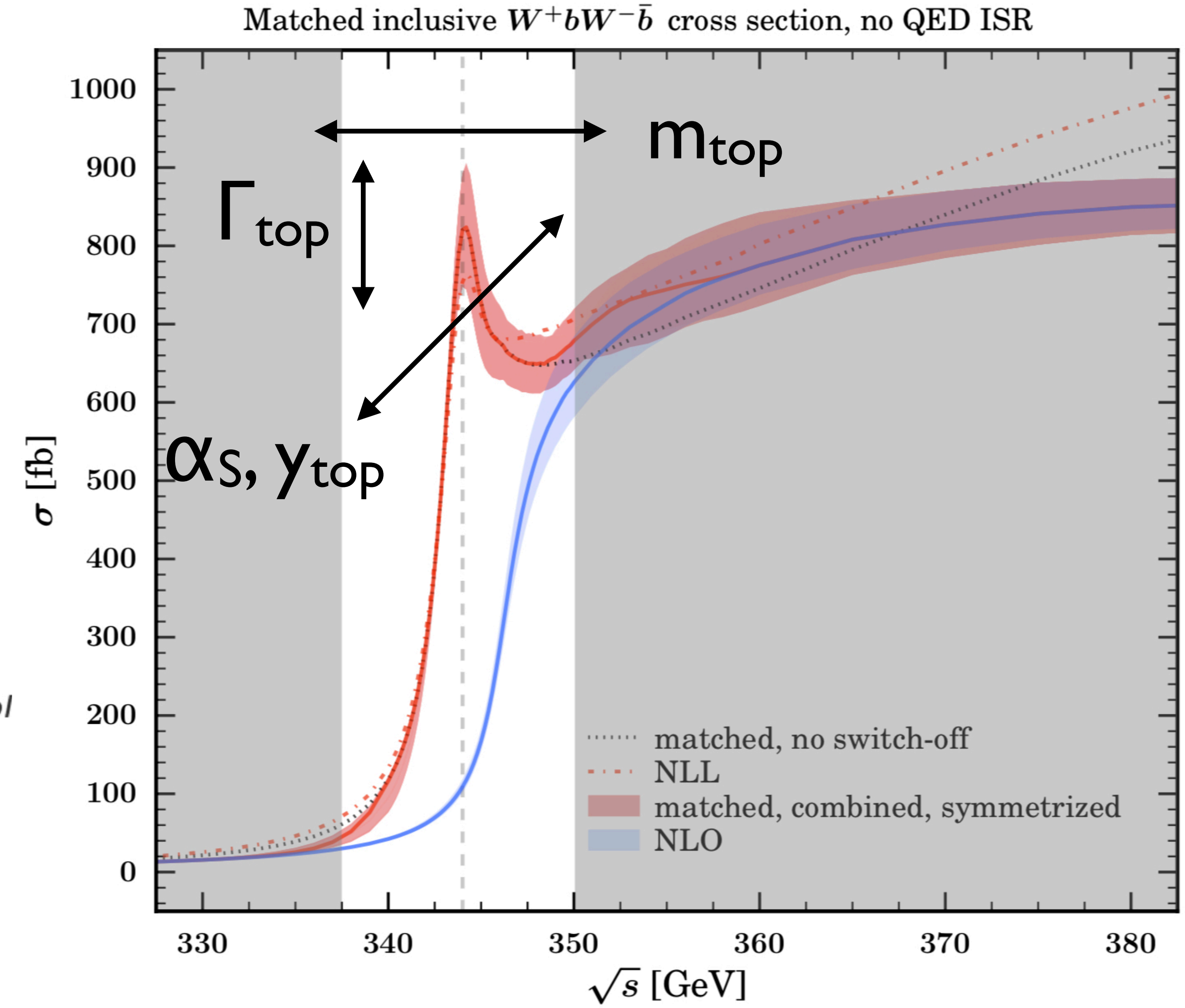

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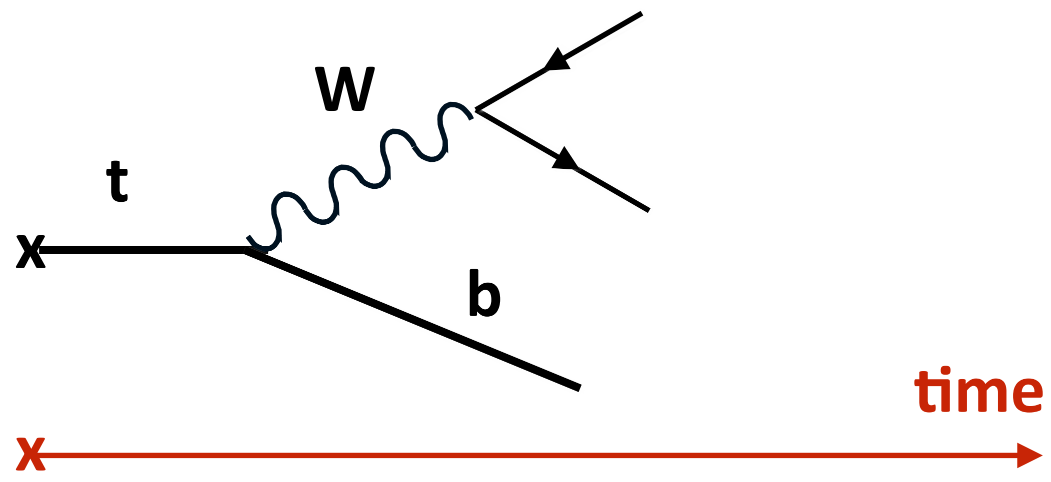
ILC scan
(F.Simon, arXiv:1902.07246)
Comparable results at FCC-ee 350, CLIC

parameter	8 point scan	10 point scan
1D fit		
m_t	($\pm$10.3(stat) $\pm$ 44(theo)) MeV	(12.2(stat) $\pm$ 40(theo)) MeV
2D fit m_t and Γ_t		
m_t	($^{+20.7}_{-24.3}$(stat) $\pm$ 45(theo)) MeV	($^{+29.7}_{-25.3}$(stat) $\pm$ 43(theo)) MeV
Γ_t	($^{+50}_{-55}$(stat) $\pm$ 32(theo)) MeV	($^{+80}_{-55}$(stat) $\pm$ 39(theo)) MeV
2D fit m_t and y_t		
m_t	($\pm$35(stat) $\pm$ 45(theo)) MeV	($^{+34}_{-31}$(stat) $\pm$ 42(theo)) MeV
y_t	$^{+0.12}_{-0.14}$(stat) $\pm$ 0.09(theo)	$^{+0.128}_{-0.112}$(stat) $\pm$ 0.132(theo)

Boosted tops in HI as QGP probe



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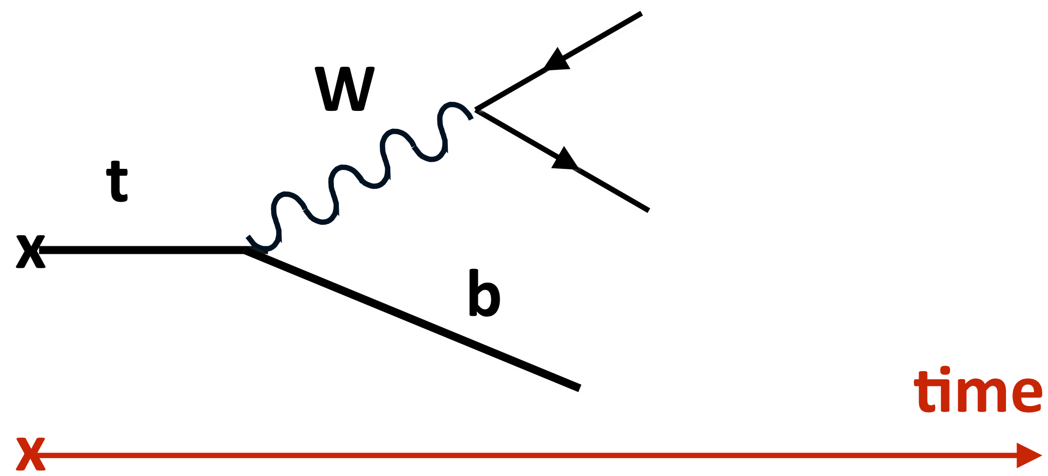

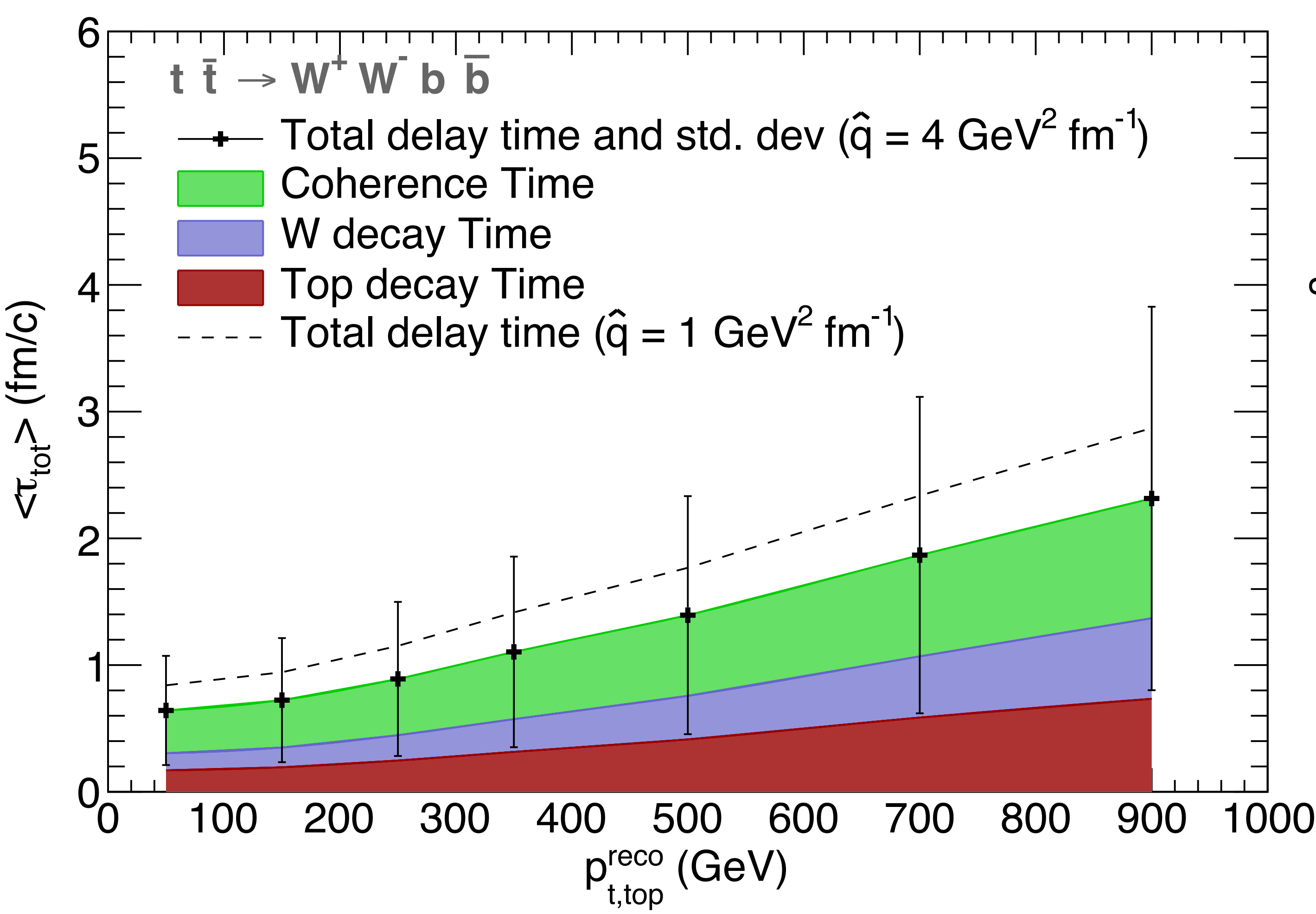

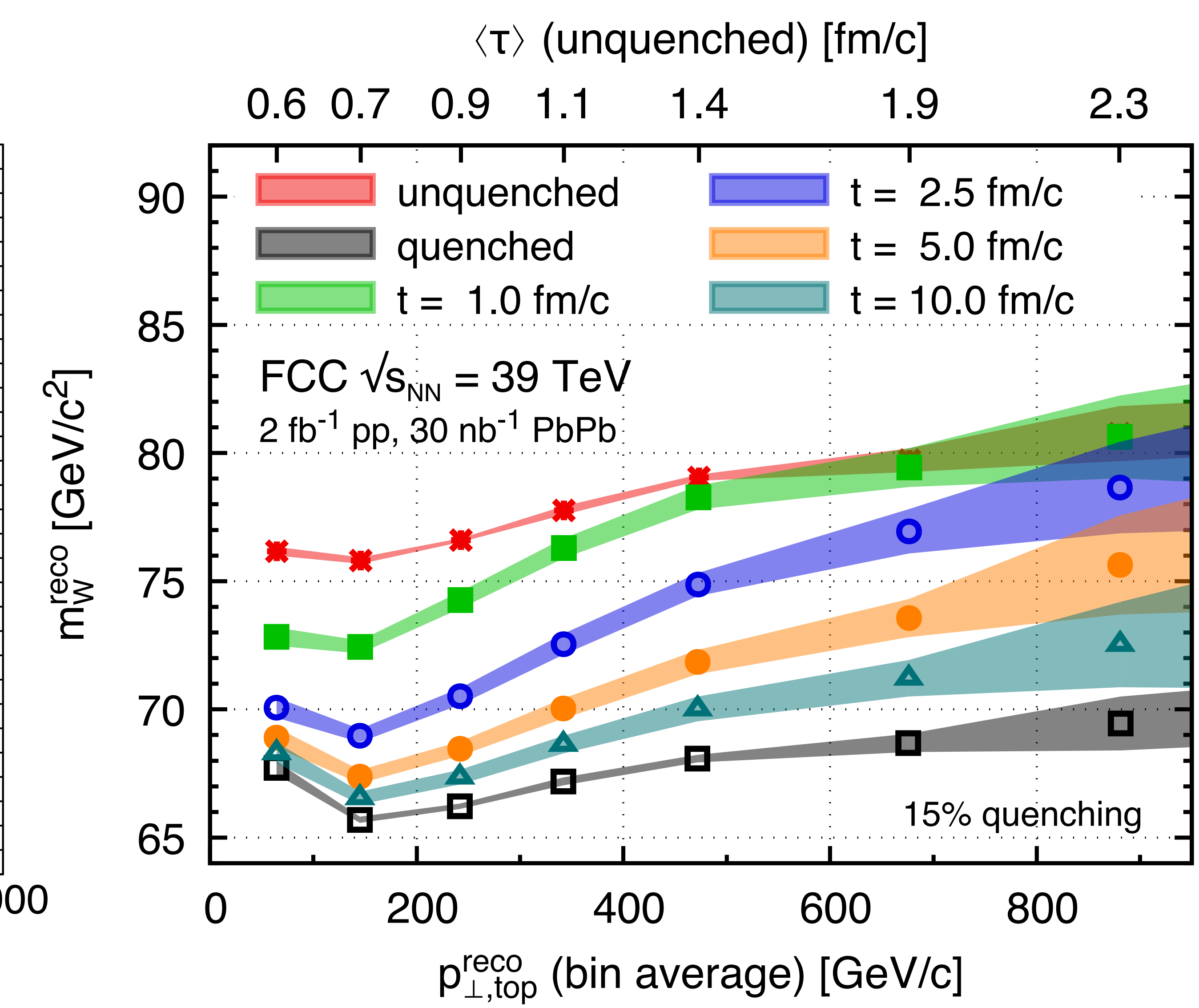

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- It plays multiple roles:
    - extraction of fundamental parameters, and input to EW precision tests
    - predictions for all production rates in pp
    - modeling of signals and backgrounds
    - probe of thermodynamical properties of QFT at high temperature and density
- Immense progress in theory, and in the reduction of systematics of LHC measurements* => suggest that QCD will be used in the future for precision physics, and will be a critical tool for a deeper exploration of the Higgs sector and EW symmetry breaking, and the searches for new physics

* see I. Watson talk