Precision calculations for BSM physics at the LHC

Michael Krämer (RWTH Aachen)

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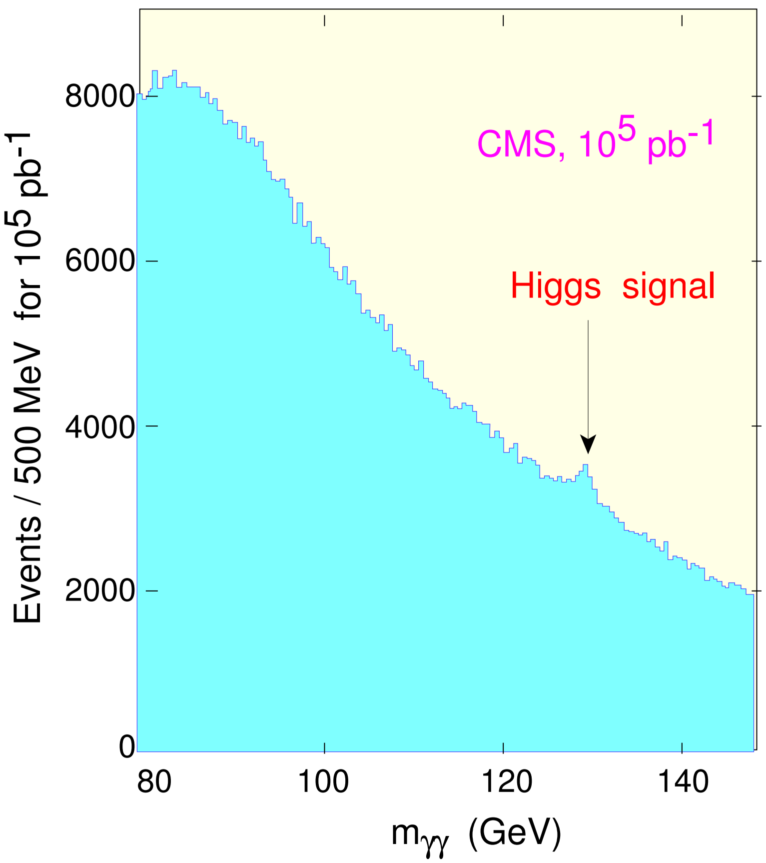
Why precision calculations for LHC physics?

- We do not need theory input for LHC discoveries



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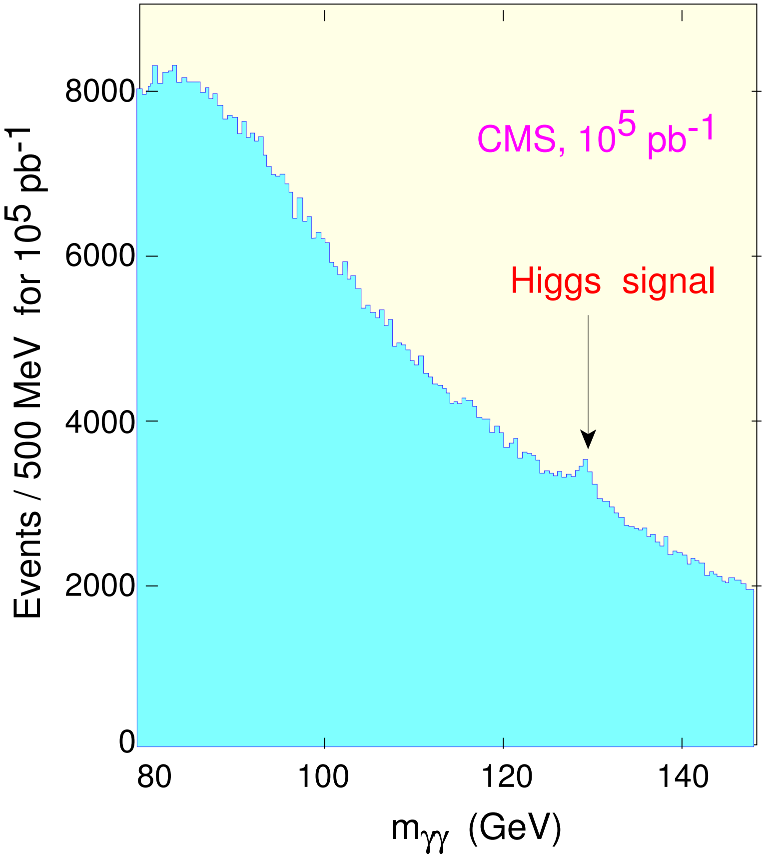

but only if we see a resonance. . .

Contents

- Why precision calculations for LHC physics?
  - lessons from the past
  - prospects: SUSY searches at the LHC

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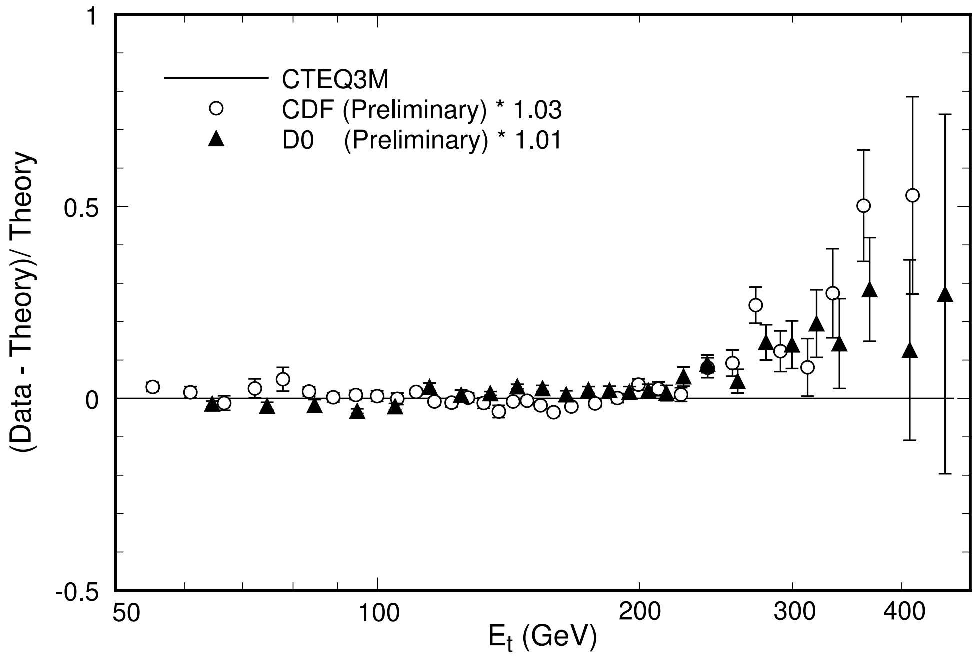
- Tevatron jet cross section at large E_T



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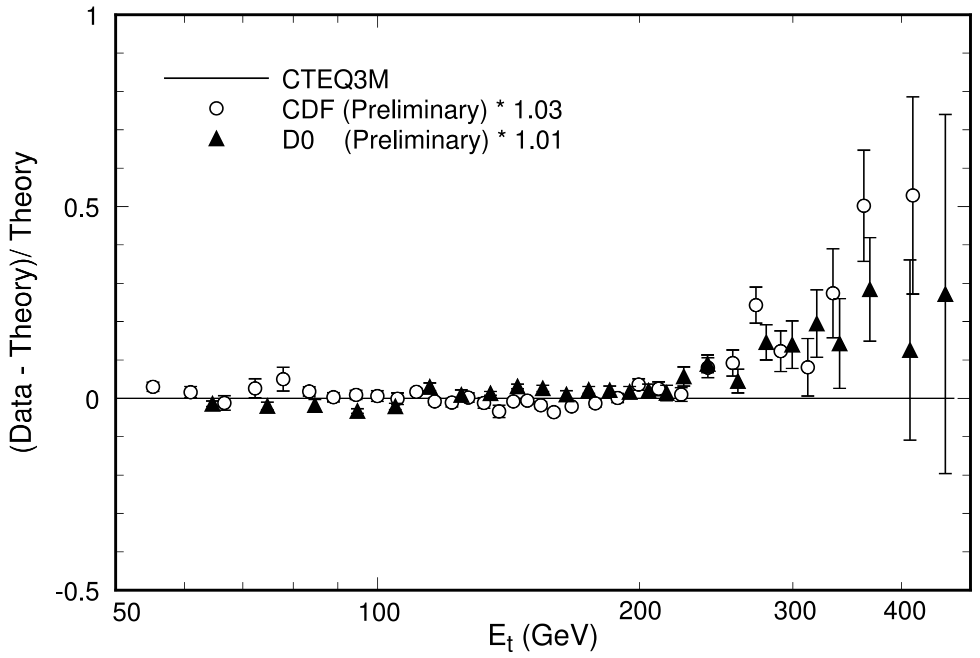
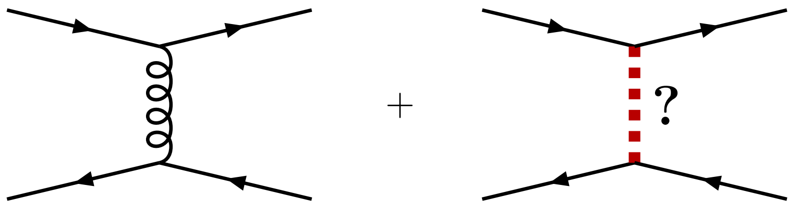


$\Rightarrow$ new physics?



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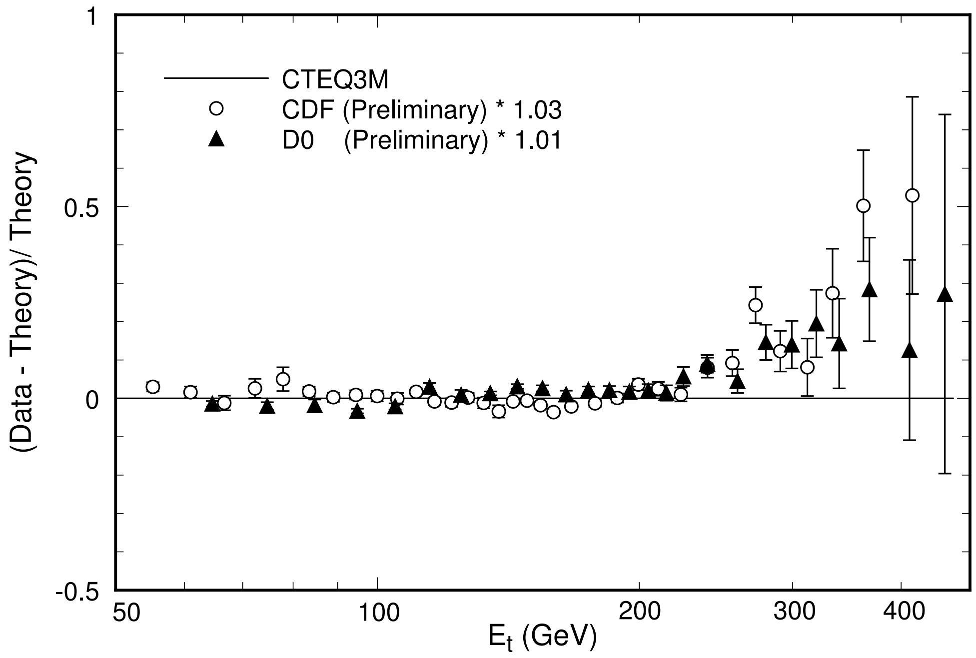

$$\mathcal{L}_{\rm BSM} \supseteq \frac{\tilde{g}^2}{M^2}\,\bar{\psi}\gamma^\mu\psi\,\bar{\psi}\gamma_\mu\psi \quad\Rightarrow\quad \frac{\rm data - theory}{\rm theory} \propto \tilde{g}^2\frac{E_T^2}{M^2}$$

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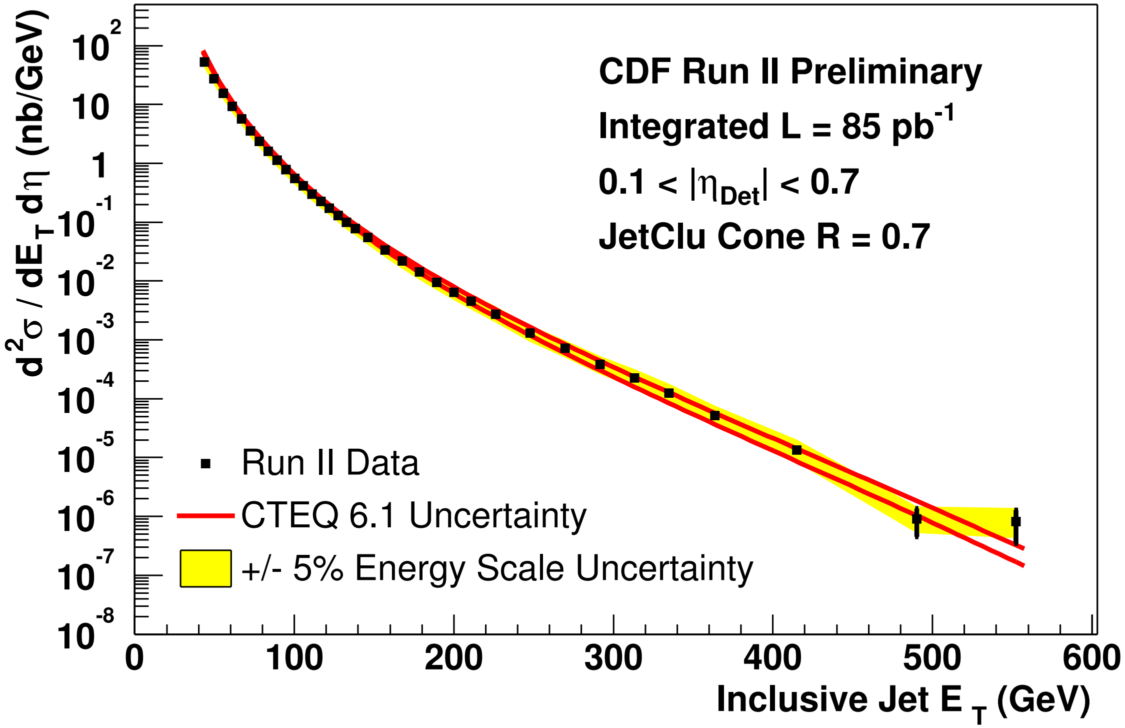
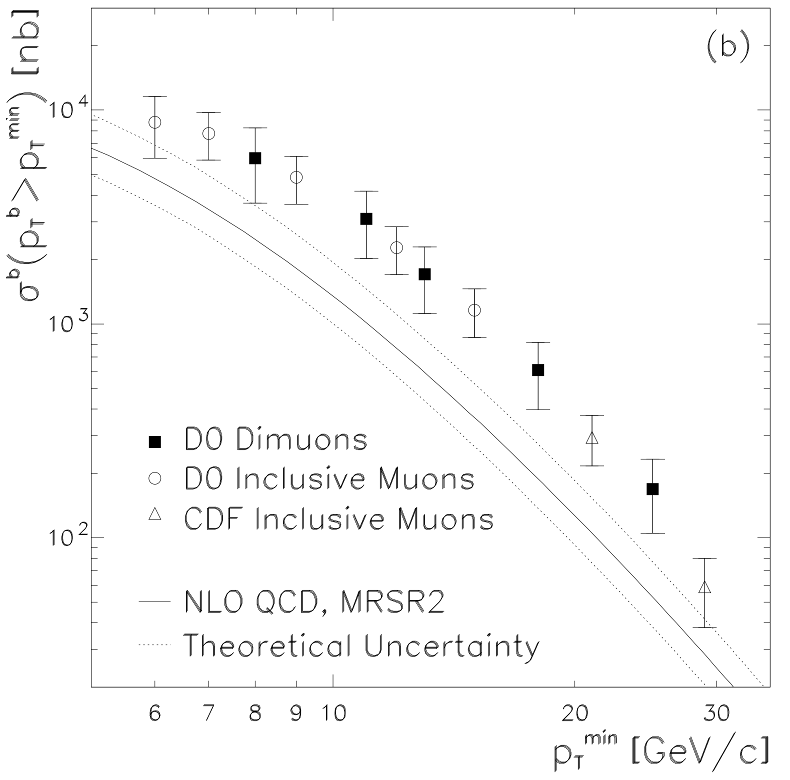


$\Rightarrow$ just QCD... (uncertainty in gluon pdf at large x)

Why precision calculations for LHC physics?

- Tevatron bottom quark cross section

[D0, PLB 487 (2000)]



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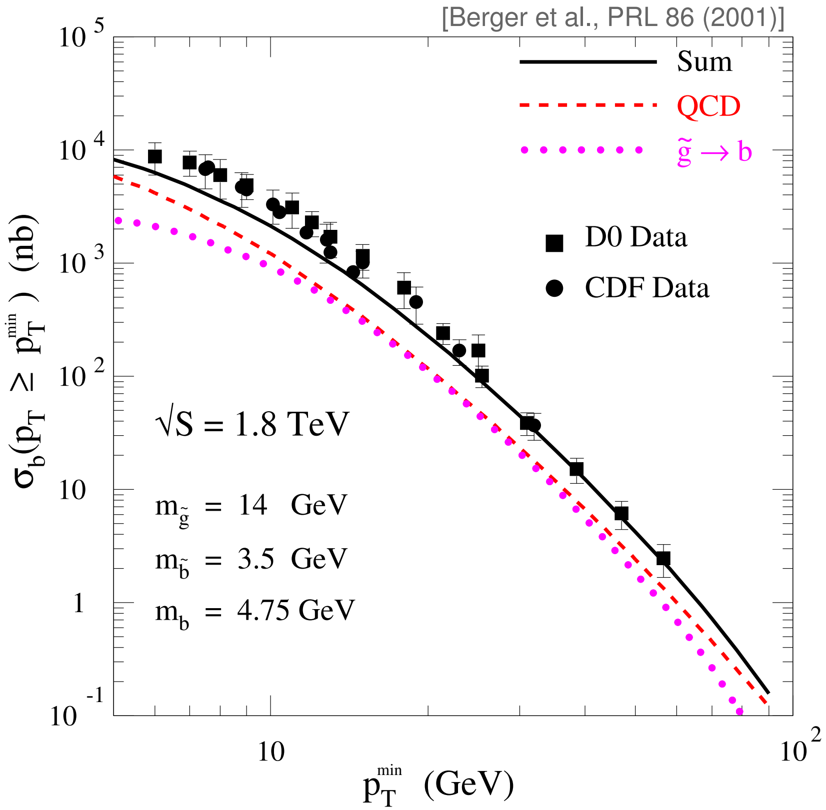
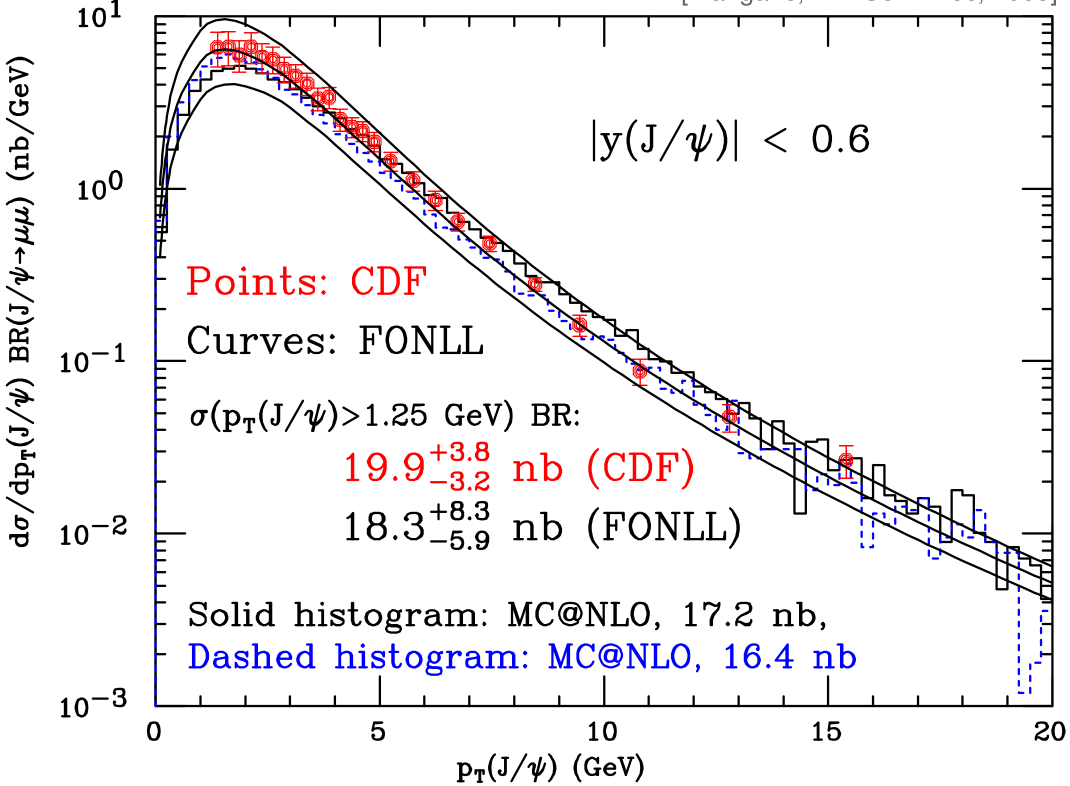


$\Rightarrow$ light gluino/sbottom production?

Why precision calculations for LHC physics?

- Tevatron bottom quark cross section

[Mangano, AIP Conf.Proc, 2005]



$\Rightarrow$ just QCD... (α_s, low-x gluon pdf, $b \longrightarrow B$ fragmentation & exp. analyses)

Why precision calculations for LHC physics?

- Signals of discovery include
  - mass peaks
  - anomalous shapes of kinematic distributions
  - excess of events after kinematic selection

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    e.g. jet production at large E_T

  – excess of events after kinematic selection

    e.g. bottom cross section

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    e.g. Higgs searches in $H \to \gamma\gamma/ZZ^*$ final states
  - anomalous shapes of kinematic distributions

    e.g. SUSY searches in multijet + $E_{\mathrm{T,miss}}$ final states
  - excess of events after kinematic selection

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- Experiments measure multi-parton final states in restricted phase space region

  $\longrightarrow$ Need flexible and realistic precision calculations

precise	$\longrightarrow$	including loops & many legs
flexible	$\longrightarrow$	allowing for exclusive cross sections & phase space cuts
realistic	$\longrightarrow$	matched with parton showers and hadronization

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BSM searches at the LHC

- Many model for new physics are addressing two problems:
  - the hierarchy/naturalness problem
  - the origin of dark matter

$\longrightarrow$ spectrum of new particles at the TeV-scale with weakly interacting & stable particle

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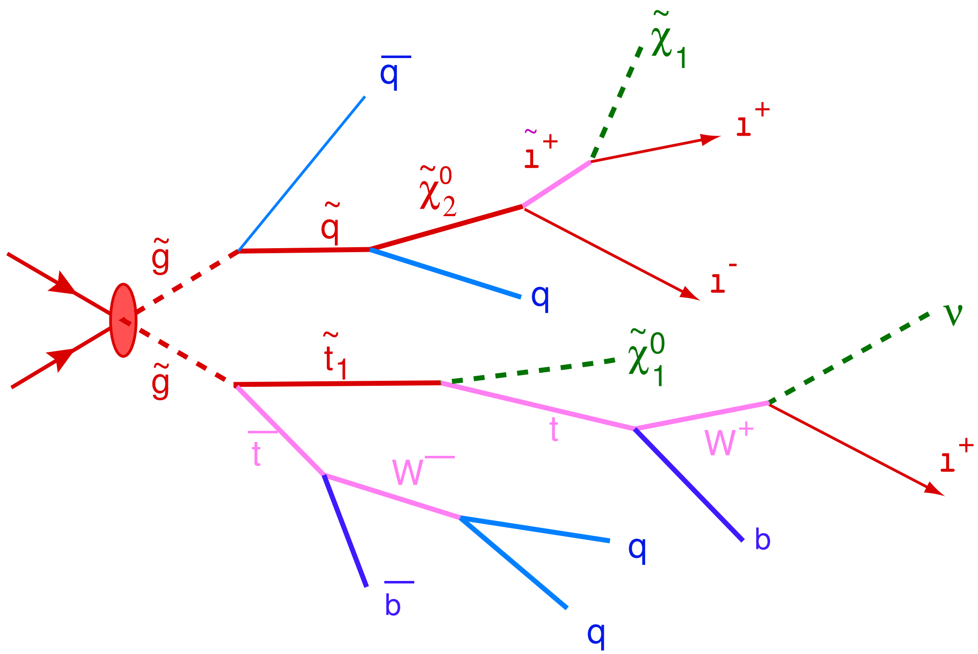
$\longrightarrow$ spectrum of new particles at the TeV-scale with weakly interacting & stable particle

$\longrightarrow$ generic BSM signature at the LHC involves cascade decays with missing energy, eg. supersymmetry

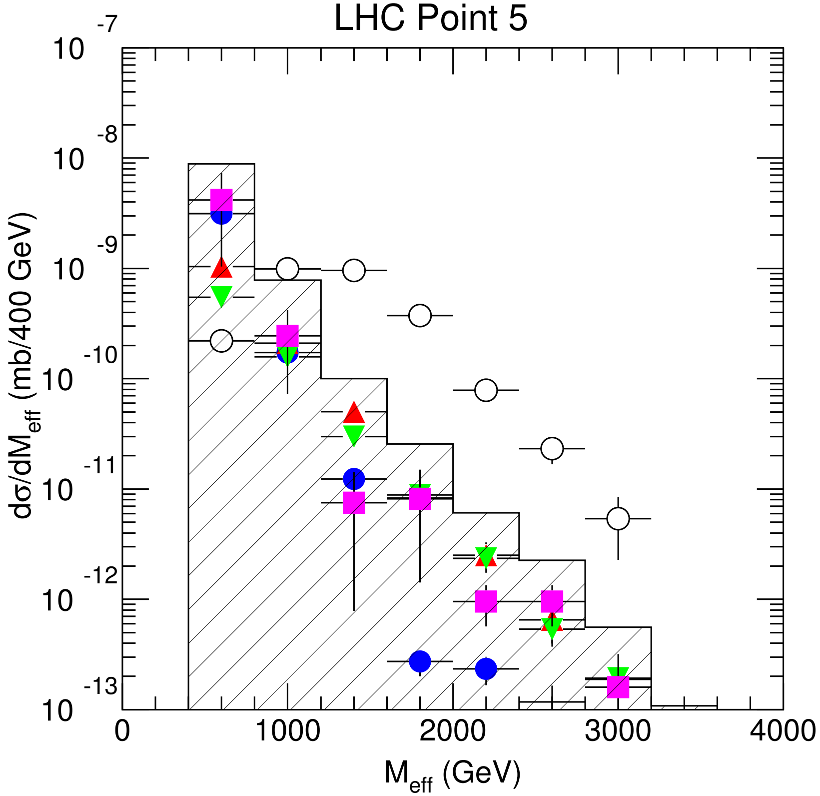


- simple discriminant for SUSY searches: effective mass

  $M_{\mathrm{eff}} = E_{\mathrm{T,miss}} + \sum_{i=1}^{4} p_{\mathrm{T}}^{\mathrm{jet}}$

- excess of events with large M_{eff}

  $\longrightarrow$ initial discovery of SUSY



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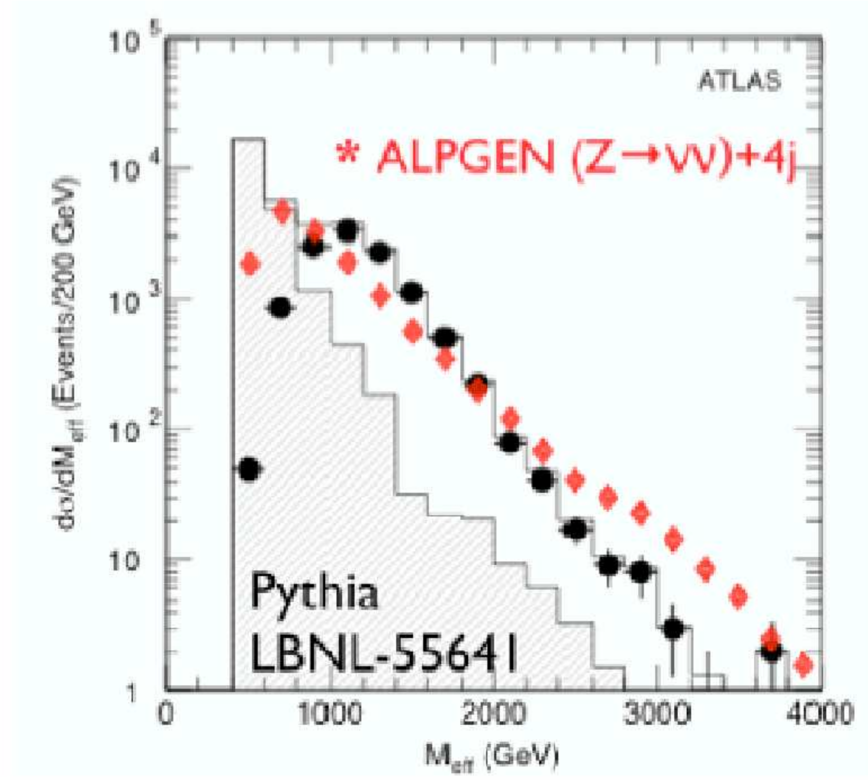

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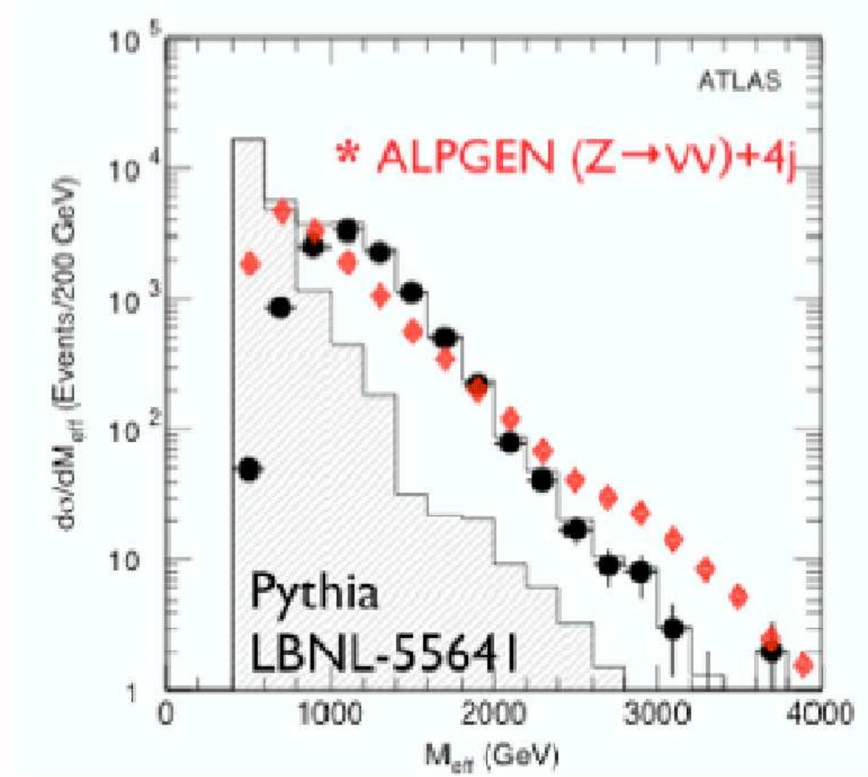

- Modern LO Monte Carlo tools predict much larger multi-jet background
- What will disagreement between Monte Carlo and data mean?
  $\longrightarrow$ Need precision NLO calculations to tell!

Precision calculations for BSM physics at the LHC

- no excess over SM expectations

  $\longrightarrow$ exclude models / set limits on model parameters

- excess in inclusive jets + $E_{\mathrm{T,miss}}$ signal (early LHC phase)

  $\longrightarrow$ discriminate BSM models

- exploring BSM models (later LHC phase)

  $\longrightarrow$ determine masses & spins

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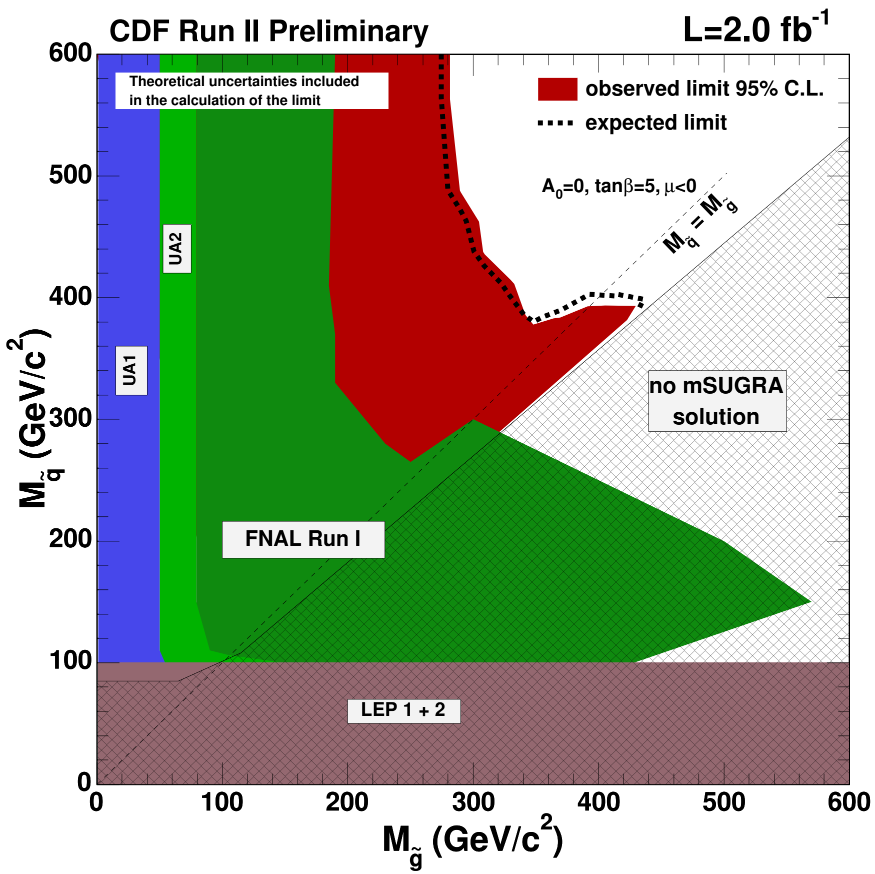
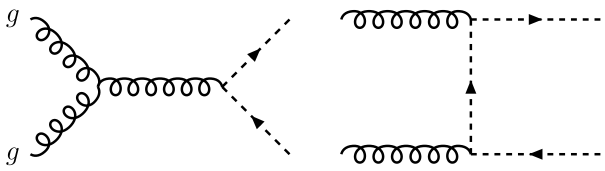


$\longrightarrow$ needs accurate theoretical predictions

SUSY particle production at hadron colliders

SUSY particles would be produced copiously at hadron colliders via QCD processes, eg.



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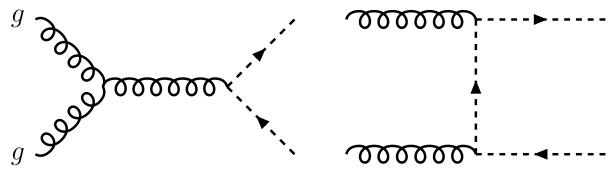
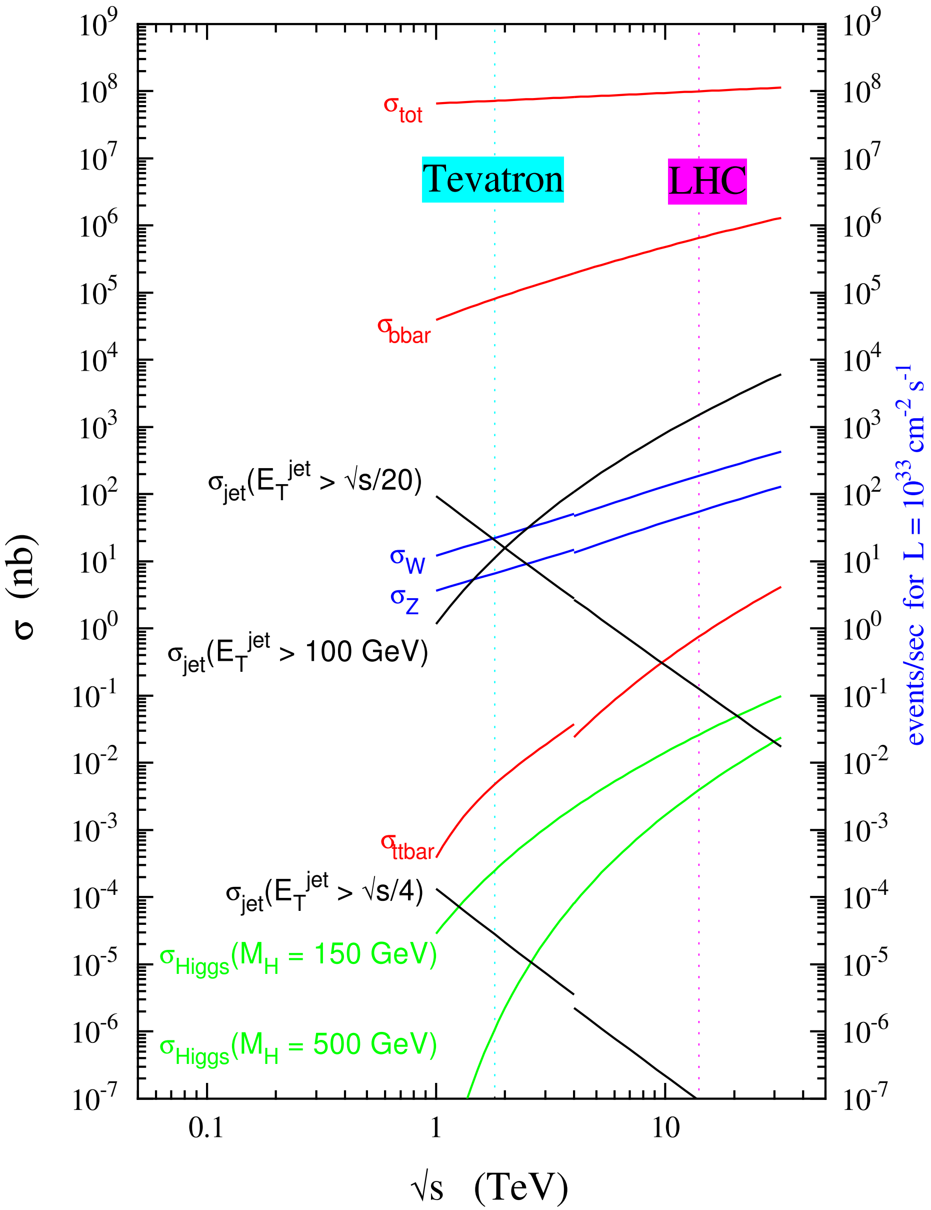


SUSY signal LHC ⟶

$\sigma(\tilde{q}\tilde{q} + \tilde{g}\tilde{g} + \tilde{g}\tilde{q}) \approx 2$ nb $\quad (M_{\tilde{q},\tilde{g}} \approx 300$ GeV)



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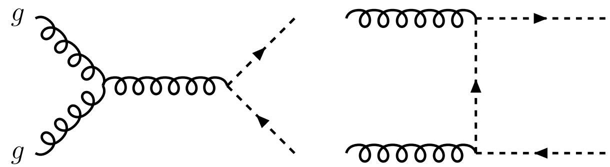

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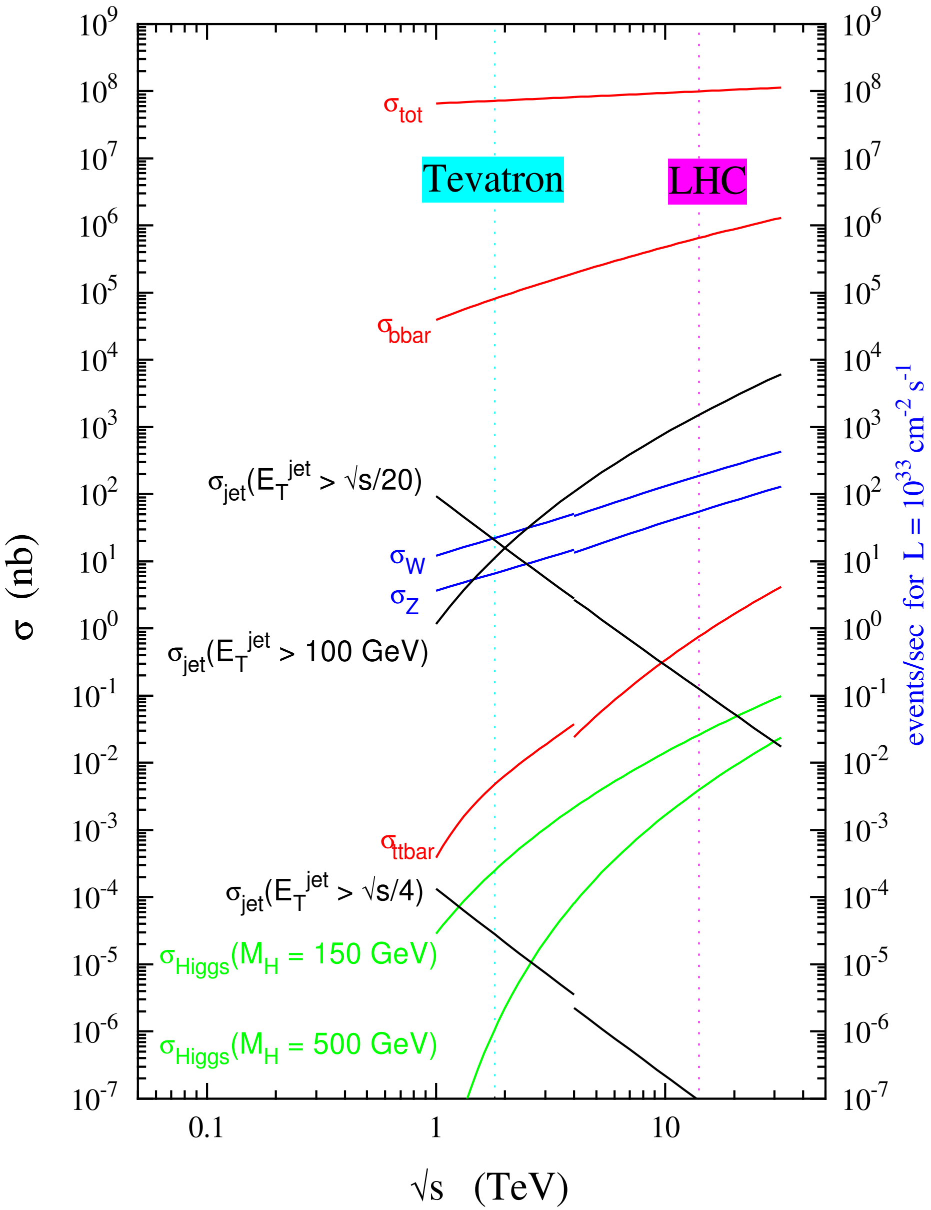

SUSY particle production at hadron colliders

- MSSM sparticle pair production at NLO (Beenakker, Höpker, MK, Plehn, Spira, Zerwas)

  — squarks & gluinos $pp/p\bar{p} \to \widetilde{q}\bar{\widetilde{q}}, \widetilde{g}\widetilde{g}, \widetilde{q}\widetilde{g}$

  — stops $pp/p\bar{p} \to \widetilde{t}\bar{\widetilde{t}}$

  — gauginos $pp/p\bar{p} \to \widetilde{\chi}^0\widetilde{\chi}^0, \widetilde{\chi}^\pm\widetilde{\chi}^0, \widetilde{\chi}^+\widetilde{\chi}^-$

  — sleptons $pp/p\bar{p} \to \widetilde{l}\widetilde{l}$

  — associated production $pp/p\bar{p} \to \widetilde{q}\widetilde{\chi}, \widetilde{g}\widetilde{\chi}$

References of LO calculations:

Kane, Leveillé, '82; Harrison, Llewellyn Smith, '83; Reya, Roy, '85; Dawson, Eichten, Quigg, '85; Baer, Tata, '85,...

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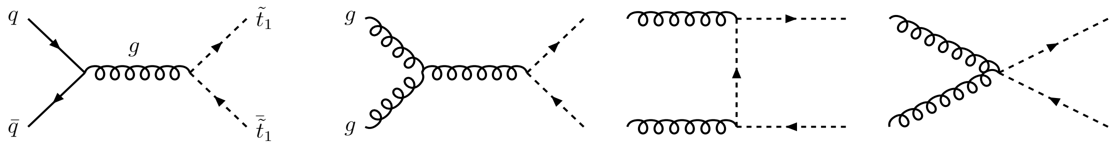
Example: Top-squark production

- LO graphs



$$\hat{\sigma}_{\rm LO}[gg] = \frac{\alpha_s^2\pi}{s}\left[\beta\left(\frac{5}{48}+\frac{31m^2}{24s}\right)+\left(\frac{2m^2}{3s}+\frac{m^4}{6s^2}\right)\log\frac{1-\beta}{1+\beta}\right] \qquad (\beta^2{=}1{-}4m^2/s)$$

$\Rightarrow$ no MSSM parameter dependence

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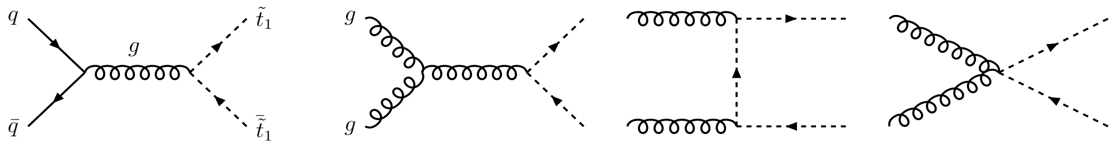

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- pp cross section: $\sigma = F_{\rm non-pert.}(\mu)\otimes\left(C_0\alpha_s^B(\mu)+C_1(\mu)\alpha_s^{B+1}(\mu)+\ldots\right)_{\rm pert.}$

Scale dependence through factorization of IR contributions and renormalization of UV contributions

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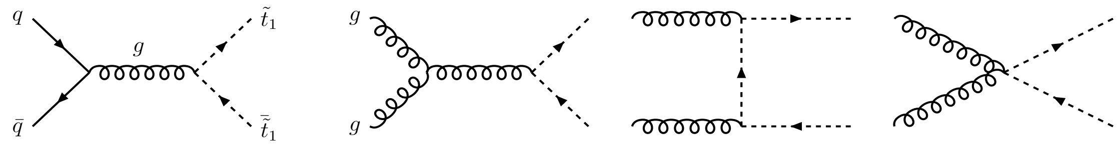

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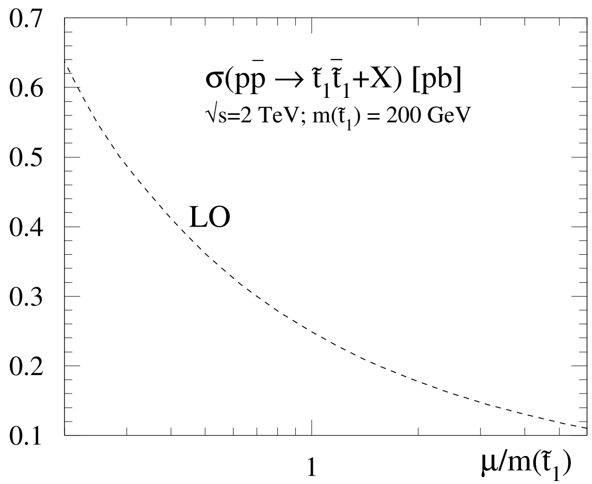
- LO scale dependence

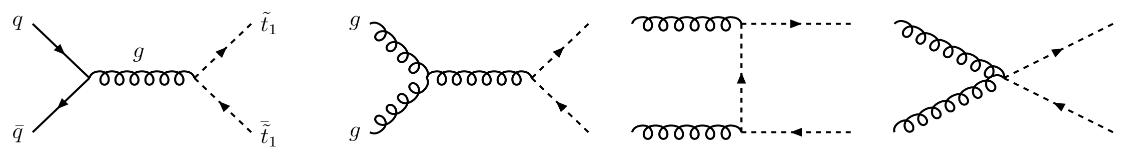


$\rightarrow$ theoretical uncertainty $\approx \pm 100\%$ at LO

$\Rightarrow$ must include NLO corrections

Example: Top-squark production

- LO graphs



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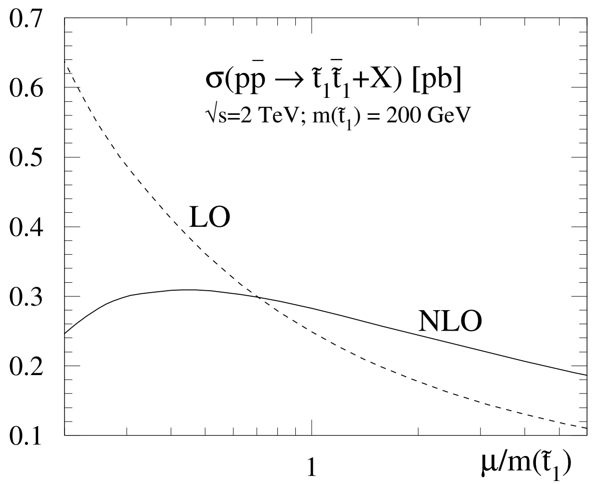
  Scale dependence through factorization of IR contributions and renormalization of UV contributions

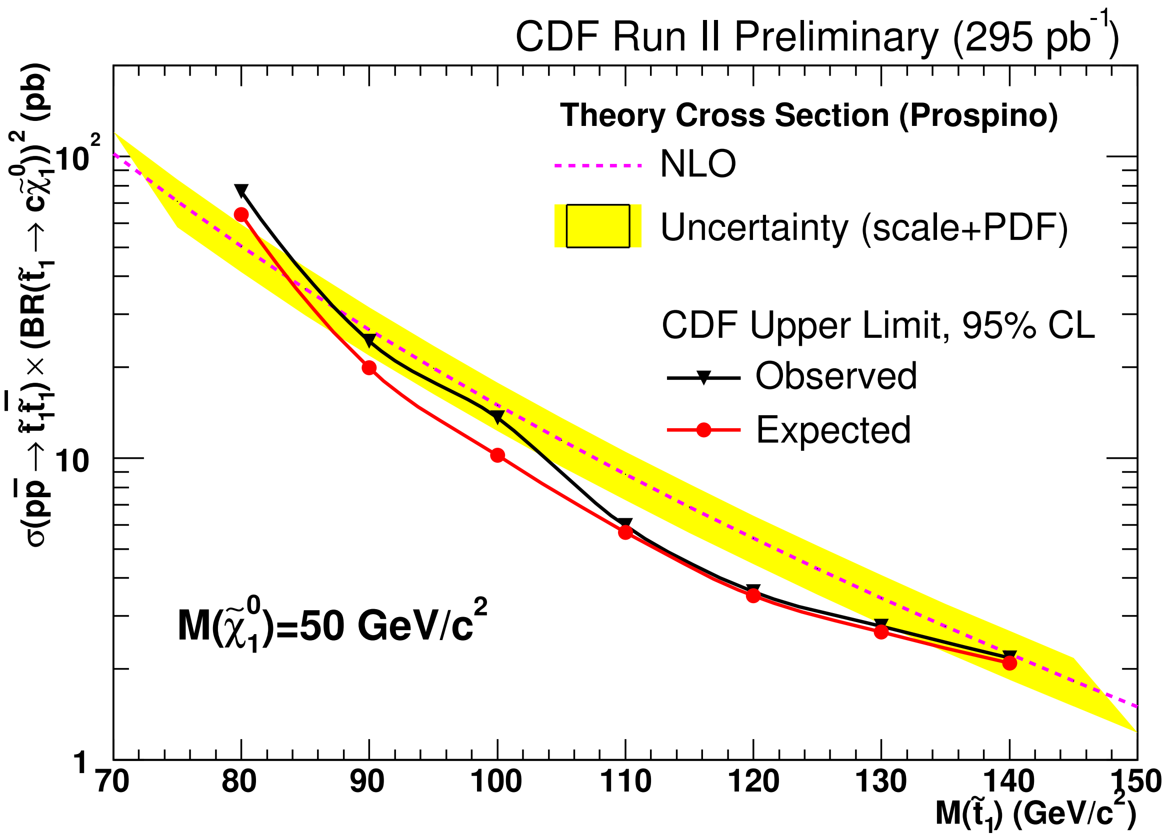
- NLO scale dependence (Beenakker, MK, Plehn, Spira, Zerwas)



$\rightarrow$ theoretical uncertainty $\approx \pm 15\%$ at NLO

Top-squark searches

- Top-squark search in $p\bar{p} \rightarrow \tilde{t}_1\bar{\tilde{t}}_1 \rightarrow c\tilde{\chi}_1^0\bar{c}\tilde{\chi}_1^0$ channel (CDF PRD 2007)



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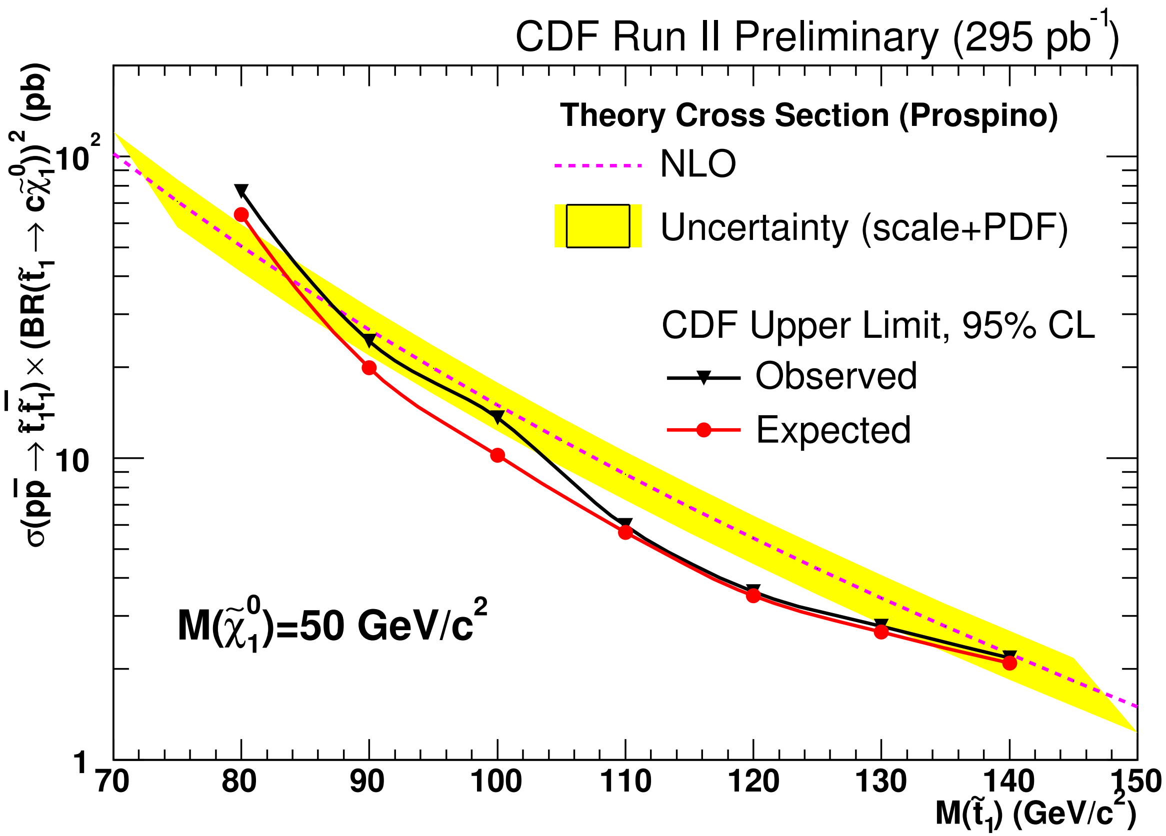

$$\Rightarrow 105\ \text{GeV} \leq M_{\tilde{t}_1} \leq 130\ \text{GeV}$$

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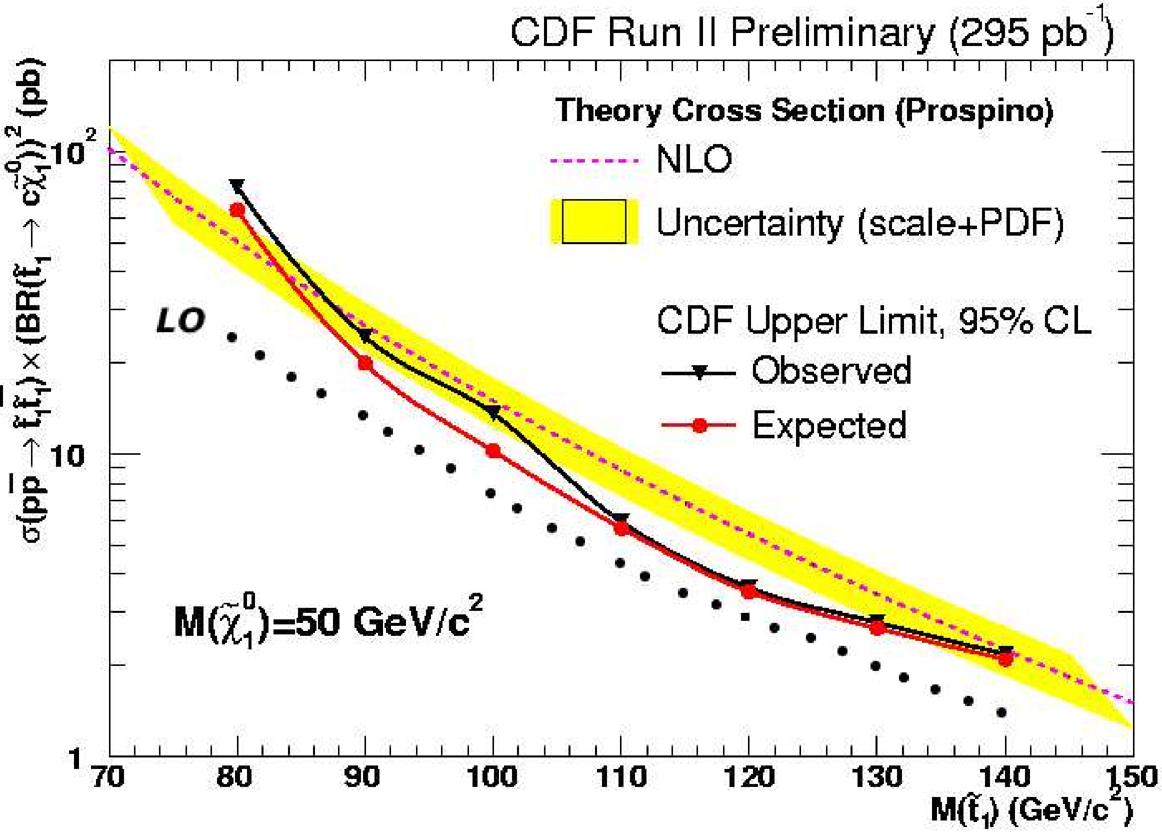
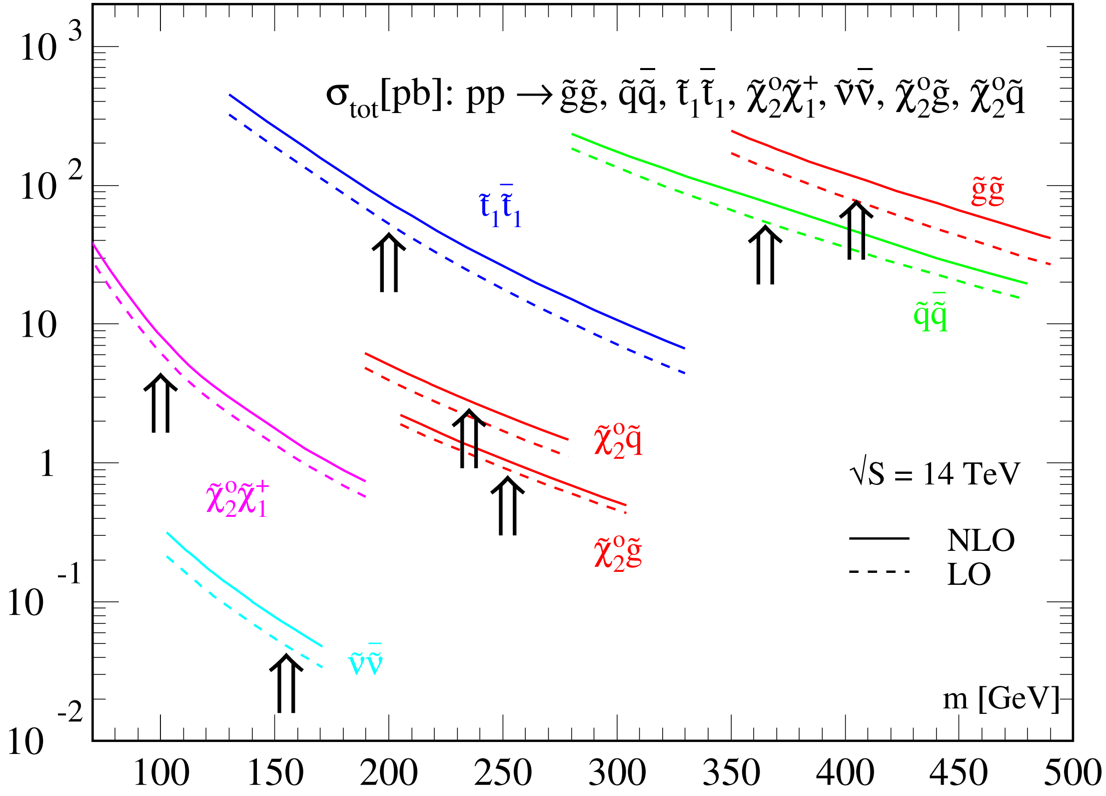


$\longrightarrow$ no exclusion based on LO cross sections

MSSM particle production at the LHC

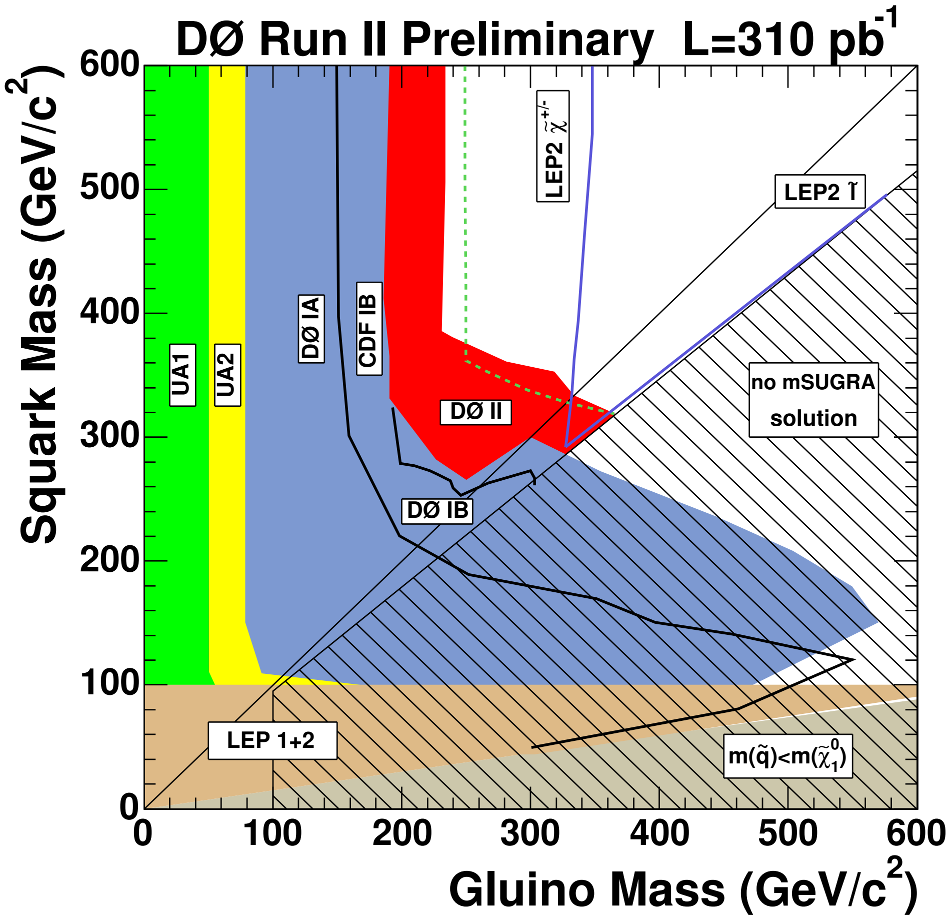
- NLO SUSY-QCD corrections for MSSM particle production at hadron colliders

⟶ public code PROSPINO (Beenakker, Höpker, MK, Plehn, Spira, Zerwas)



References: Beenakker, Höpker, Spira, Zerwas, 1995, 1997; Beenakker, MK, Plehn, Spira, Zerwas, 1998; Baer, Hall, Reno, 1998; Beenakker, Klasen, MK, Plehn, Spira, Zerwas, 1999; Beenakker, MK, Plehn, Spira, Zerwas, 2000; Berger, Klasen, Tait, 1999-2002; Beenakker, MK, Plehn, Spira, Zerwas, 2007

Current limits on sparticle masses



- mass limits (roughly)

$$M_{\tilde{g}} \gtrsim 250 \text{ GeV}$$
$$M_{\tilde{q}} \approx M_{\text{gluino}} \gtrsim 400 \text{ GeV}$$
$$M_{\tilde{t}_1} \gtrsim 100 \text{ GeV}$$
$$M_{\tilde{\chi}_1^0} \gtrsim 50 \text{ GeV}$$
$$M_{\tilde{\chi}_1^\pm} \gtrsim 100 \text{ GeV}$$
$$M_{\text{sleptons}} \gtrsim 100 \text{ GeV}$$

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- excess in inclusive jets + $E_{\mathrm{T,miss}}$ signal (early LHC phase)

  $\longrightarrow$ discriminate BSM models

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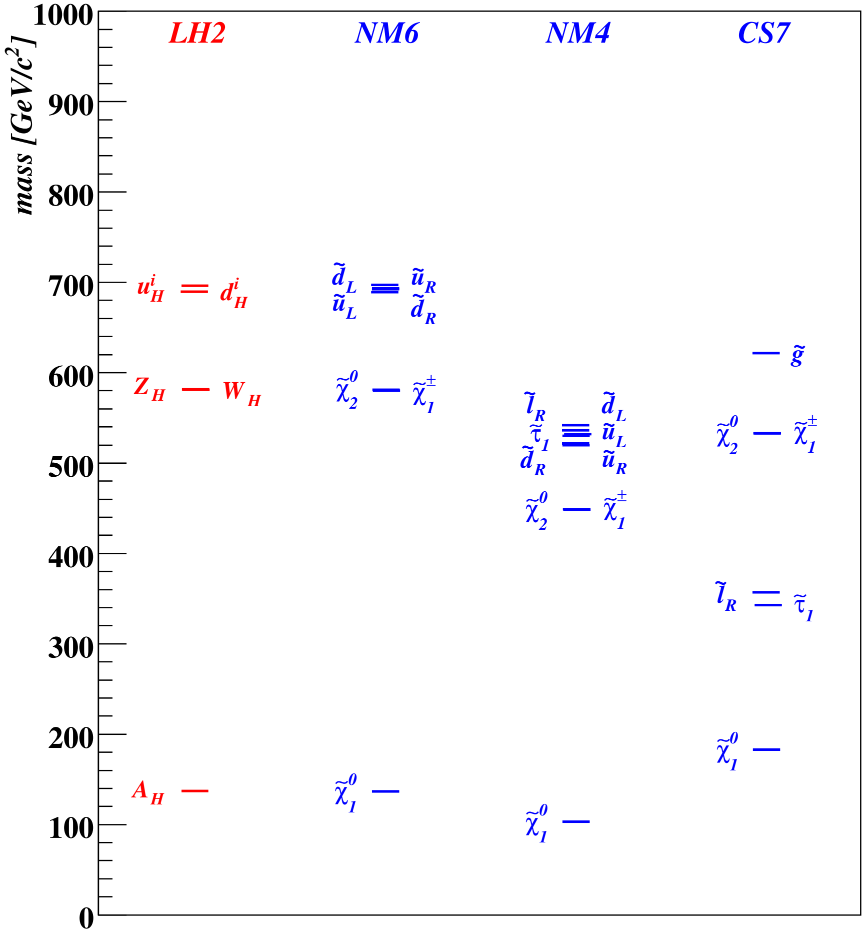
  "look-alike models" (Hubisz, Lykken, Pierini, Spiropulu)



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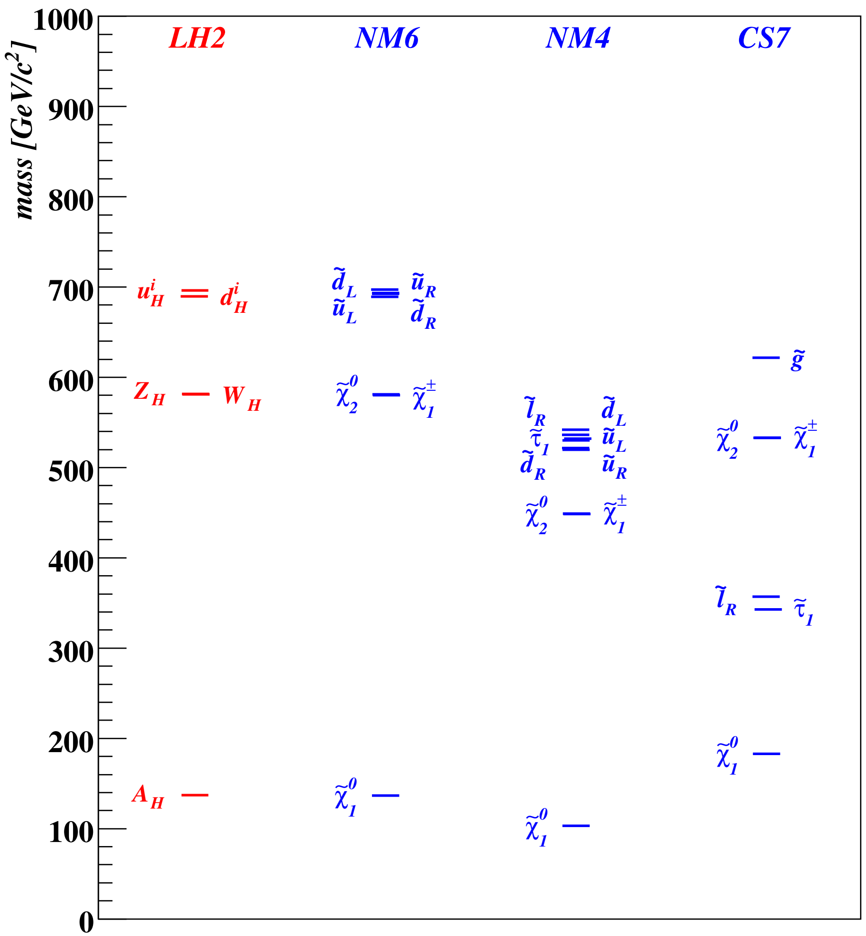

- Little Higgs model LH2 and SUSY models NM4 and CS7 give same number of events after cuts
- "twin models" LH2 and NM6 (SUSY) have different cross sections and event counts

  $\longrightarrow$ distinguish models with same spectrum but different spins through event count

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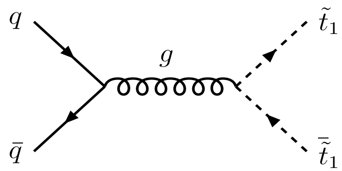
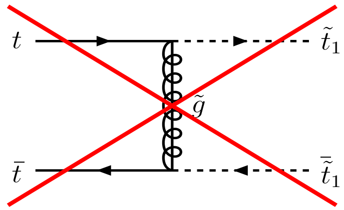
"ancient wisdom": cross sections depend on spin, e.g.

$$q + \bar{q} \longrightarrow \widetilde{q} + \bar{\widetilde{q}}$$





$$\hat{\sigma}_{\mathrm{LO}}[q\bar{q} \longrightarrow \widetilde{q}\bar{\widetilde{q}}] = \frac{\alpha_s^2 \pi}{s} \frac{4}{27} \beta^3 \quad (\beta^2 = 1 - 4m^2/s)$$

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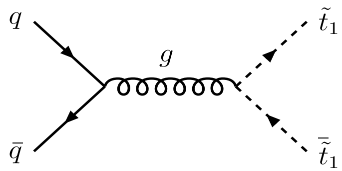
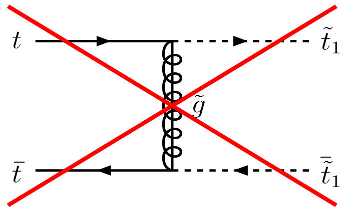




$$\hat{\sigma}_{\mathrm{LO}}[q\bar{q} \longrightarrow \widetilde{q}\widetilde{\bar{q}}] = \frac{\alpha_s^2 \pi}{s} \frac{4}{27} \beta^3 \quad (\beta^2 = 1 - 4m^2/s)$$

c.f. top production:

$$\hat{\sigma}_{\mathrm{LO}}[q\bar{q} \longrightarrow Q\overline{Q}] = \frac{\alpha_s^2 \pi}{s} \frac{8}{27} \frac{(s + 2m^2)}{s^2} \beta$$

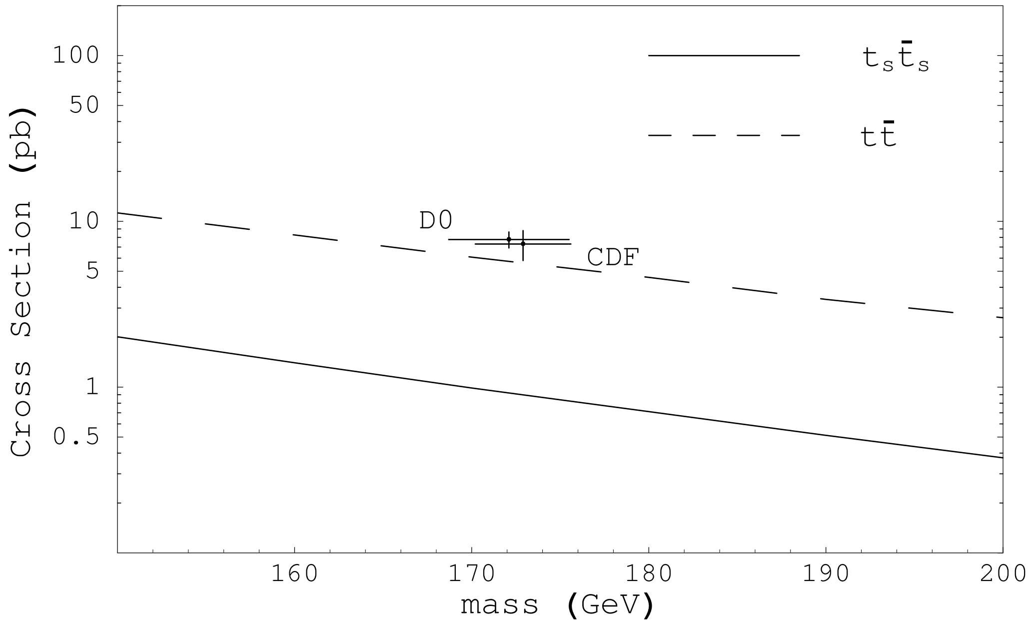
$\longrightarrow \sigma^{\mathrm{top}} / \sigma^{\mathrm{stop}} \sim 10$ at the Tevatron

Precision calculations for BSM physics at the LHC

- excess in inclusive jets + $E_{\mathrm{T,miss}}$ signal (early LHC phase)
  $\longrightarrow$ discriminate BSM models

  "ancient wisdom": cross sections depend on spin

(Kane, Petrov, Shao, Wang)



$\longrightarrow$ no production of scalar quarks (assuming same mass and couplings as top. . .)

Precision calculations for BSM physics at the LHC

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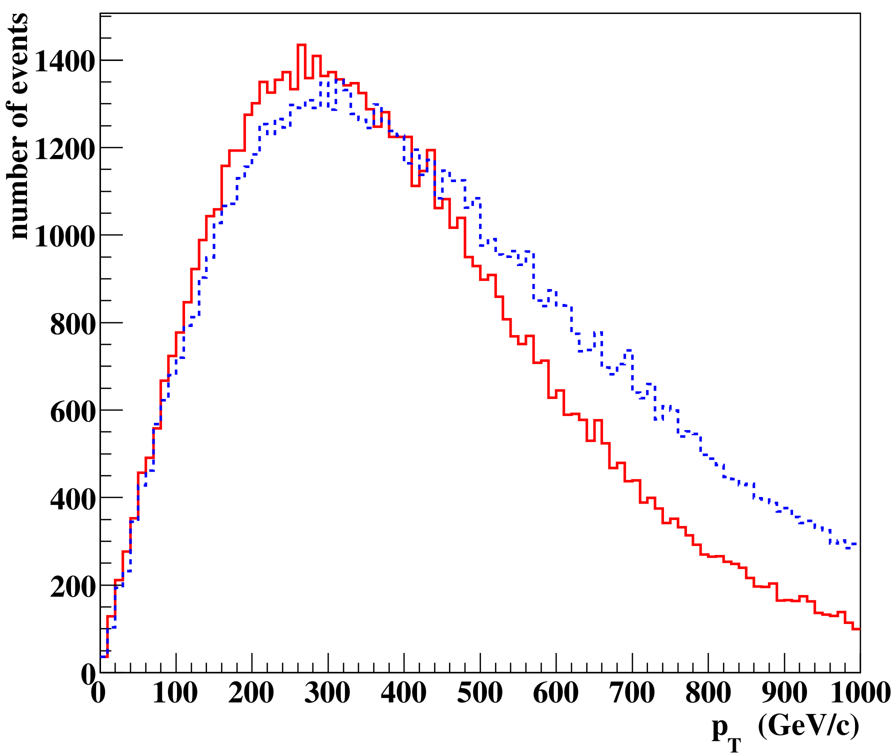
  how to discriminate "look-alike models"? (Hubisz, Lykken, Pierini, Spiropulu)



– consider ratios of event counts, e.g.
  $\sigma(p_T > 250, 500, \ldots$ GeV$)/\sigma$
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  $\longrightarrow$ normalization important

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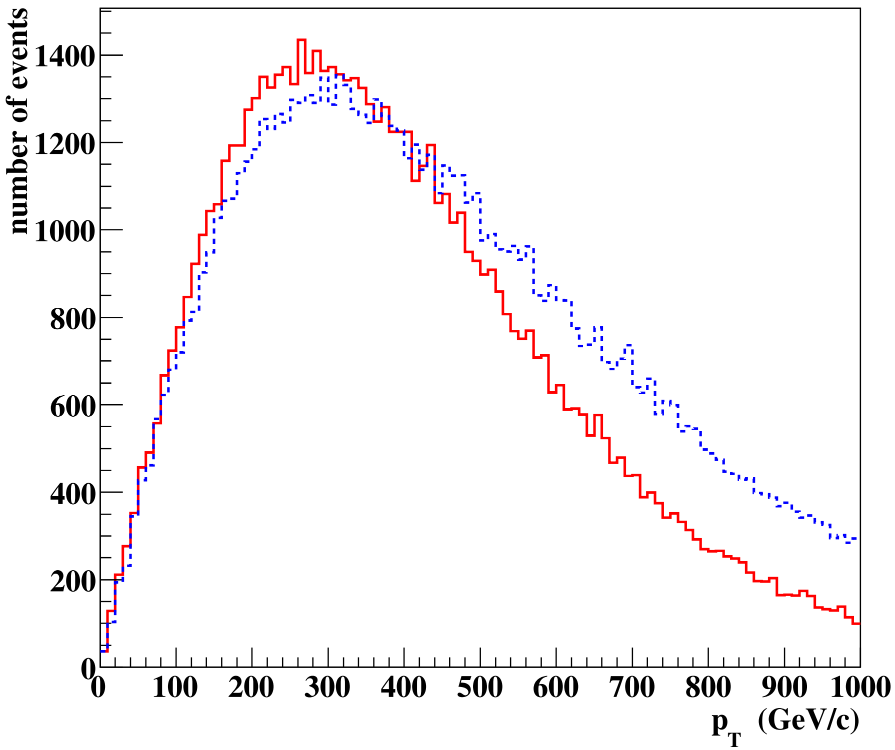

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$$K \equiv \frac{\sigma^{\mathrm{NLO}}(pp \to \tilde{t}\bar{\tilde{t}})}{\sigma^{\mathrm{LO}}(pp \to \tilde{t}\bar{\tilde{t}})} = \begin{cases} 1.4 & (p_T > 100 \text{ GeV}) \\ 0.5 & (p_T > 1000 \text{ GeV}) \end{cases}$$

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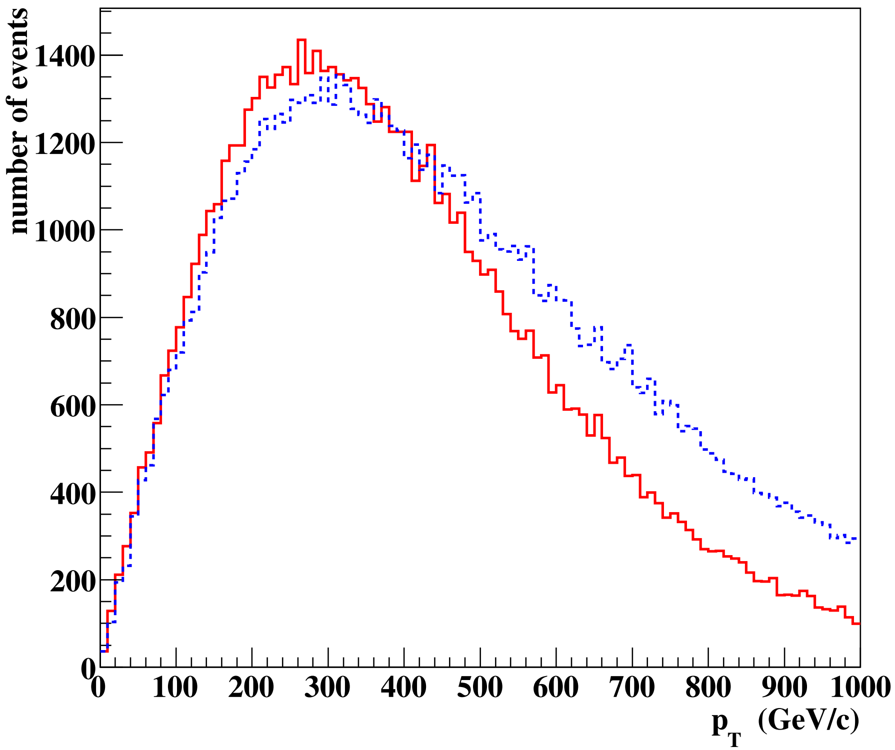

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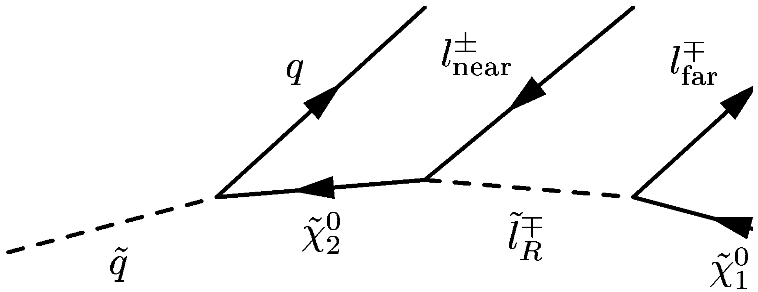
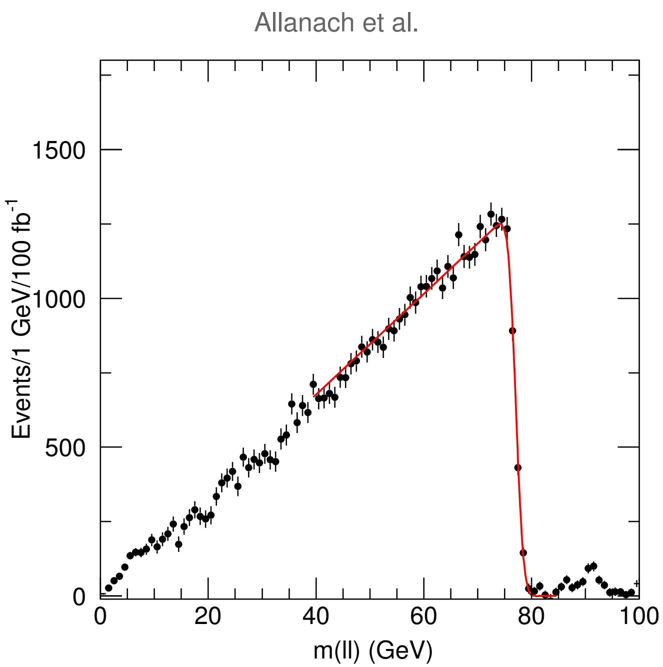
$\longrightarrow$ no proper tools to perform realistic NLO analysis of BSM decay chains

Precision calculations for BSM physics at the LHC

- exploring BSM models (later LHC phase)
  $\longrightarrow$ determine masses & spins

Mass measurements from cascade decays, e.g.





$\longrightarrow$ kinematic endpoint $\quad (m_{ll}^{\rm max})^2 = (m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_{\rm R}})(m^2_{\tilde{l}_{\rm R}} - m^2_{\tilde{\chi}^0_1})/(m^2_{\tilde{l}_{\rm R}})$

sensitive to mass differences

Precision calculations for BSM physics at the LHC

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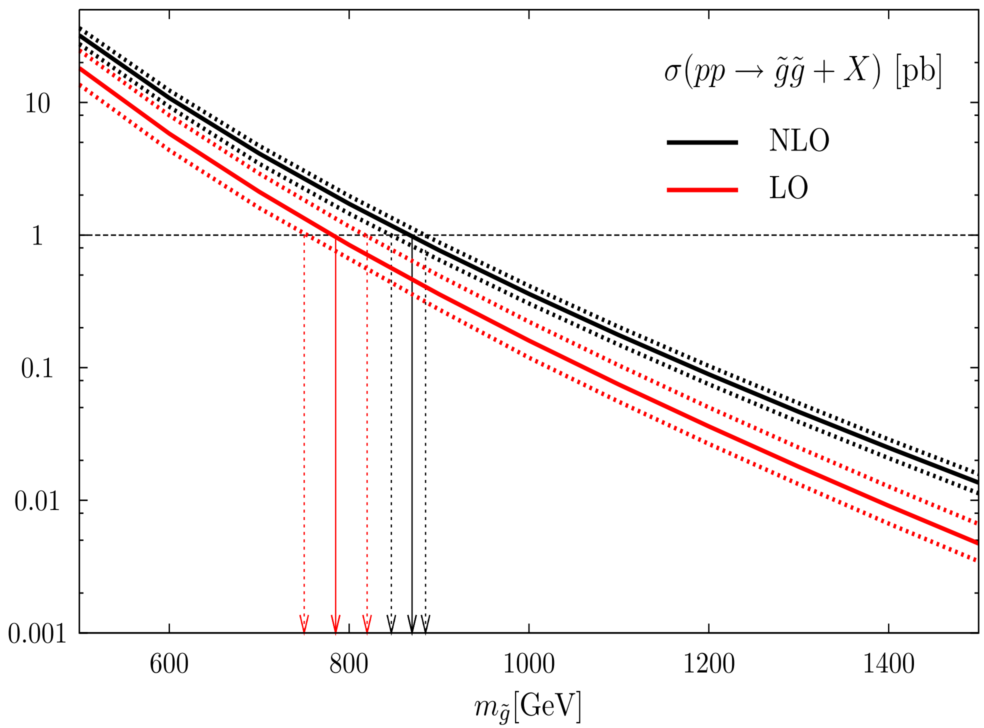
  Mass measurements from total rate, e.g. gluino mass in SUSY models with heavy scalars (FP dark matter scenarios)



$$m_{\text{gluino}} = \begin{cases} 785 \pm 35 & \text{(LO)} \\ 870 \pm 15 & \text{(NLO)} \end{cases}$$

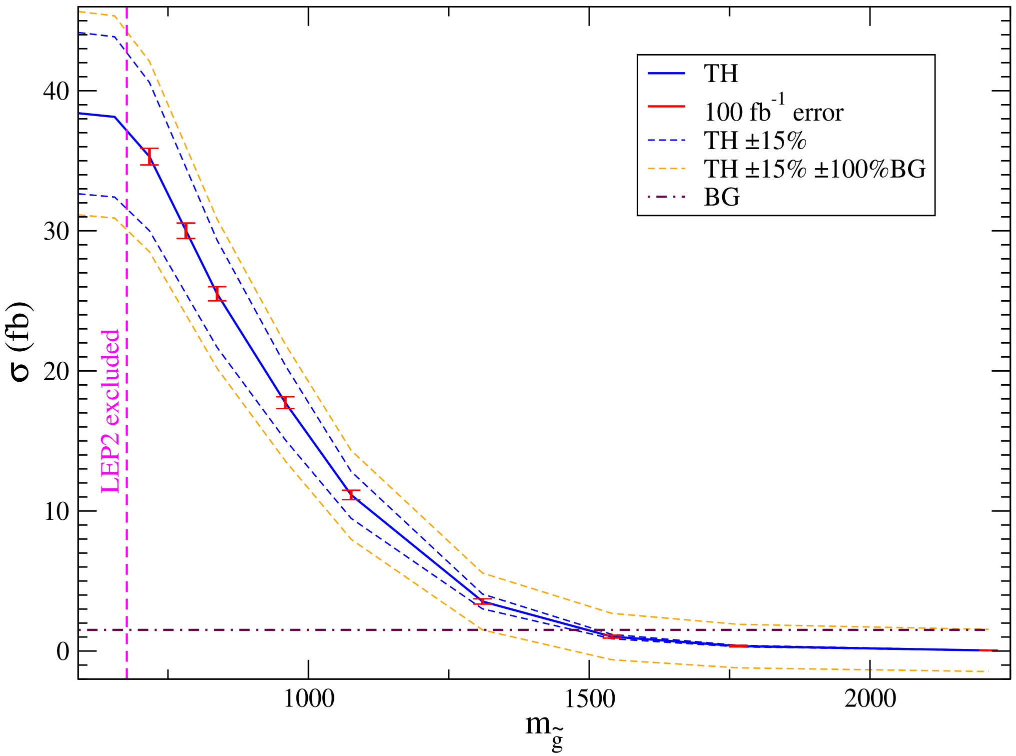
Precision calculations for BSM physics at the LHC

- exploring BSM models (later LHC phase)

  $\longrightarrow$ determine masses & spins

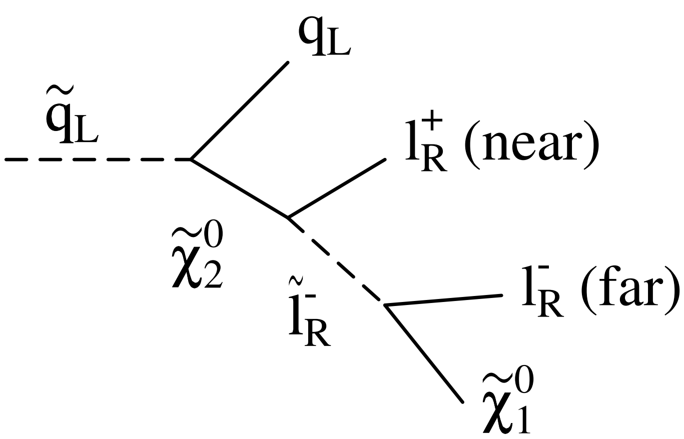
Mass measurements from total rate, e.g. gluino mass in SUSY models with heavy scalars (FP dark matter scenarios)

(Baer, Barger, Shaunghnessy, Summy, Wang)

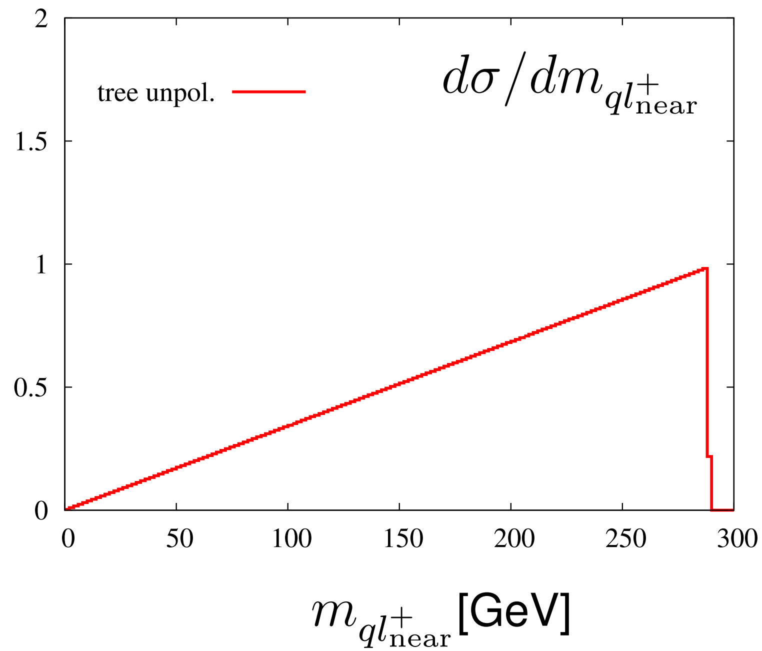


$\longrightarrow \Delta m_{\text{gluino}} = \pm 8\%$

- exploring BSM models (later LHC phase)
  $\longrightarrow$ determine masses & spins



no spin correlations:



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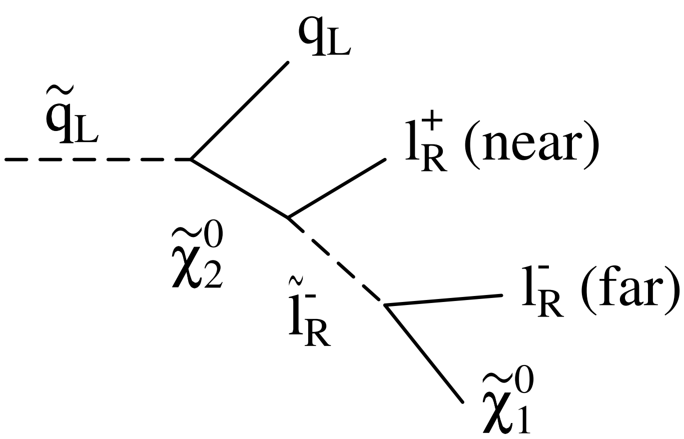
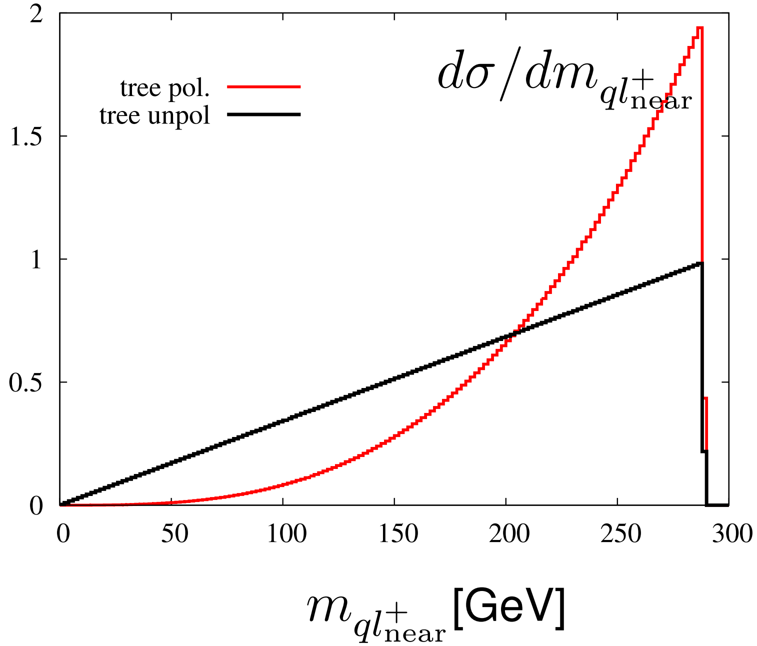


with spin correlations:



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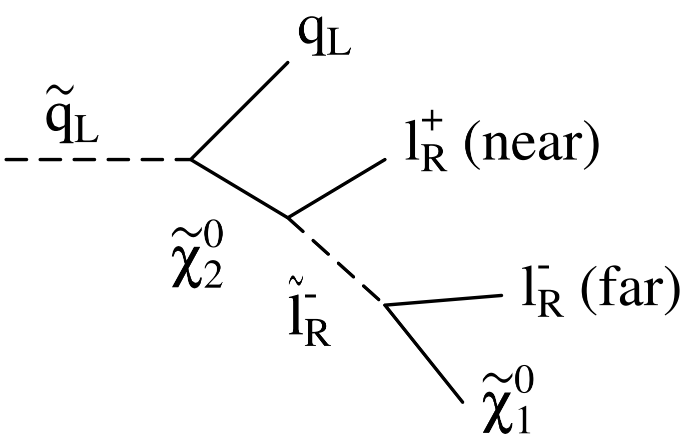

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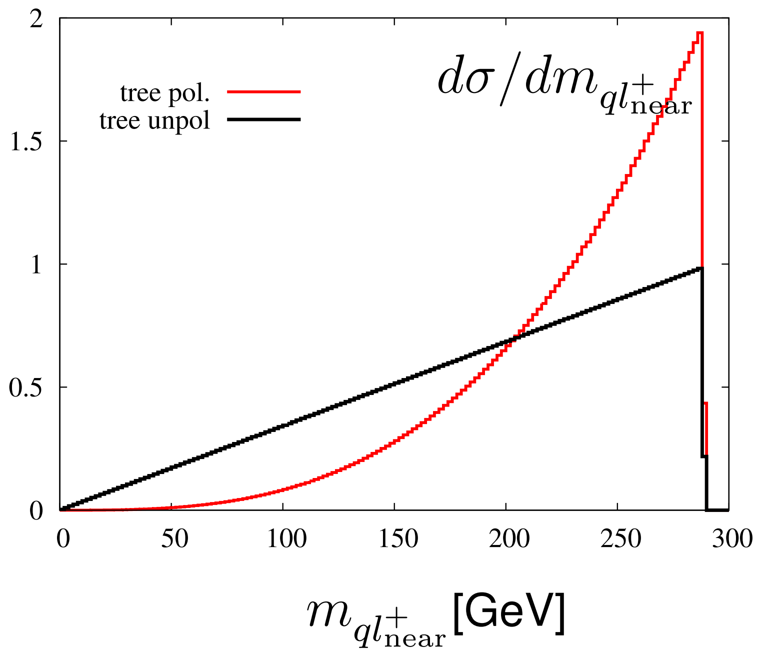

cannot determine $m_{ql^+_{\rm near}}$ distribution experimentally

$\longrightarrow$ consider charge asymmetry $A = (d\sigma/dm_{ql^+} - d\sigma/dm_{ql^-})/(d\sigma/dm_{ql^+} + d\sigma/dm_{ql^-})$

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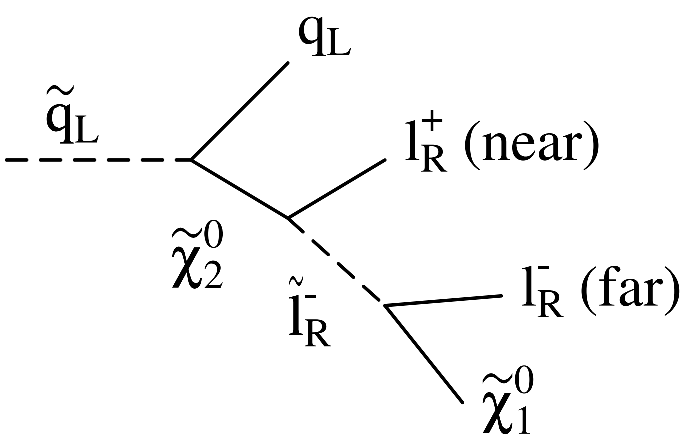

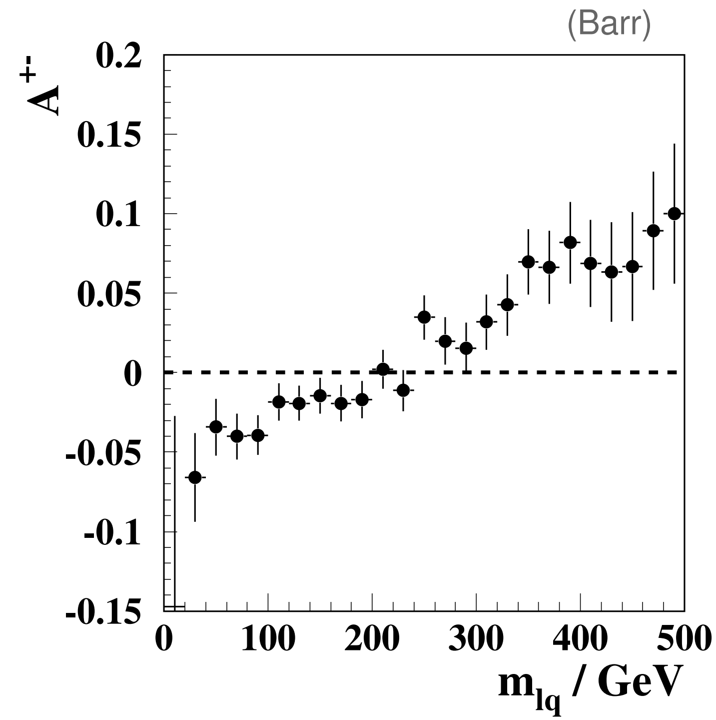

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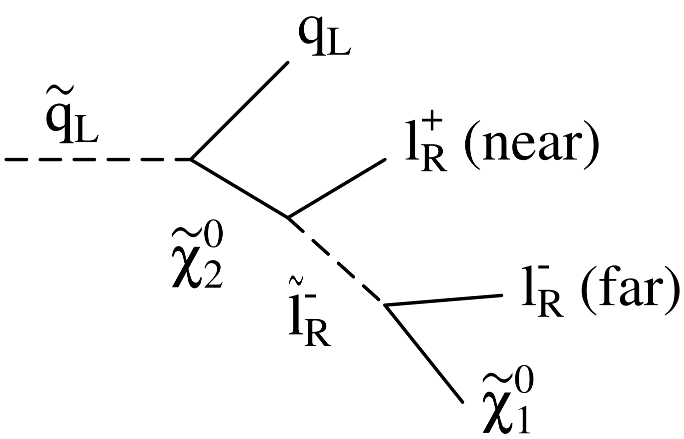

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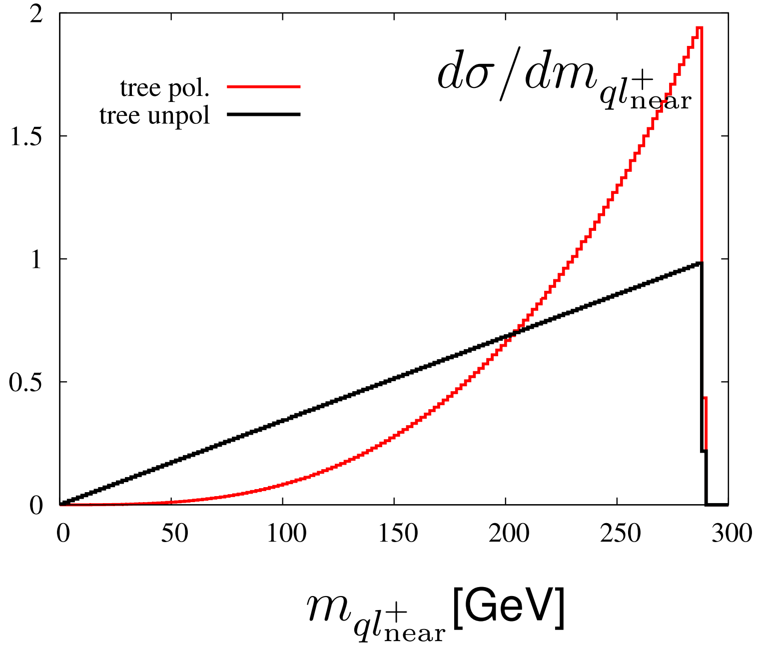

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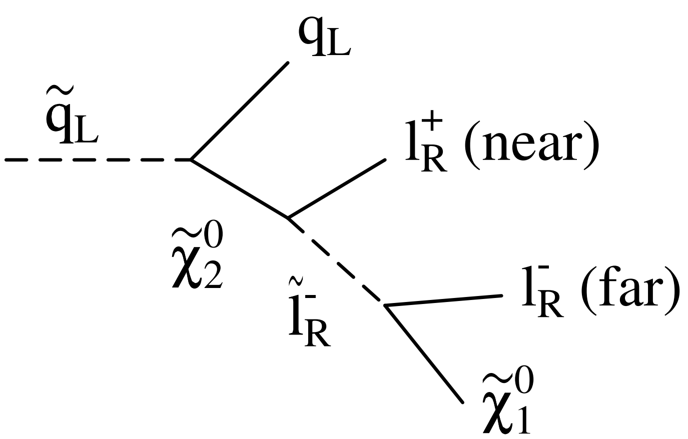
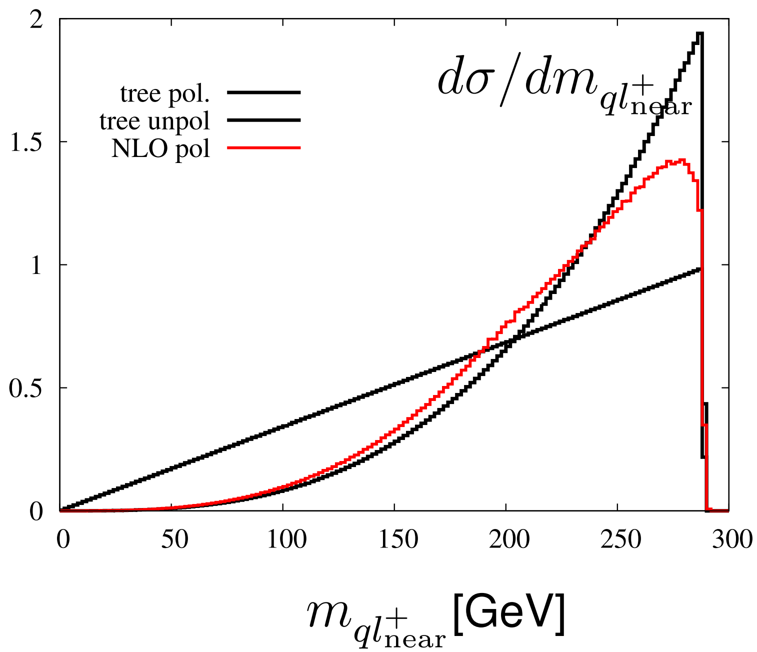


with spin correlations @ NLO:



$\longrightarrow$ radiative corrections affect shape of distributions (Horsky, MK, Mück, Zerwas)

Precision calculations for BSM physics at the LHC

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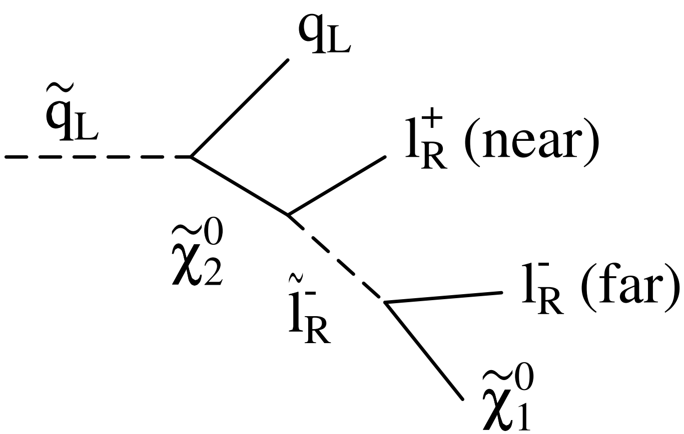

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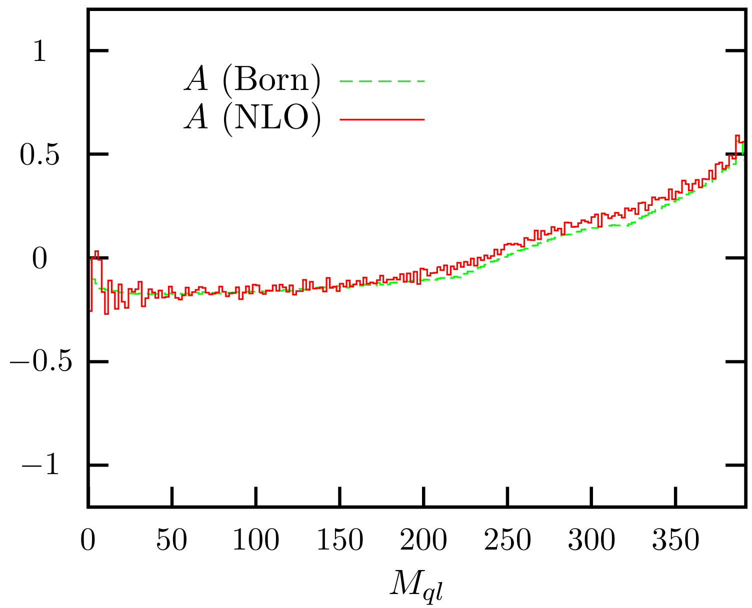


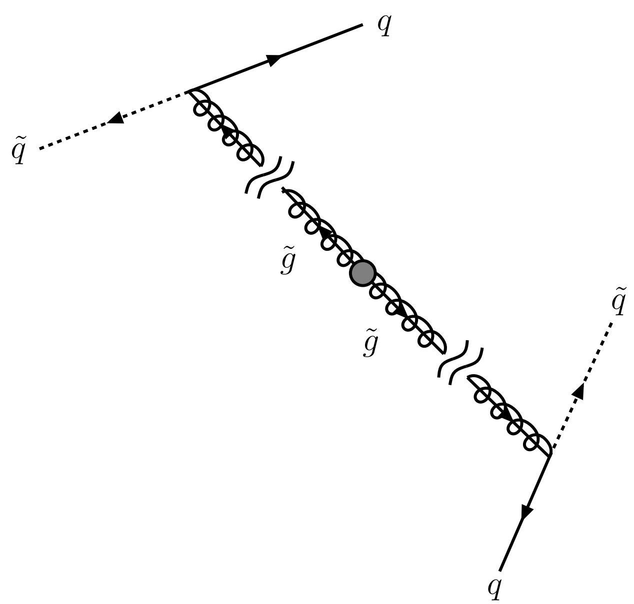
consider charge asymmetry $A = (d\sigma/dm_{ql^+} - d\sigma/dm_{ql^-})/(d\sigma/dm_{ql^+} + d\sigma/dm_{ql^-})$

$\longrightarrow$ radiative corrections cancel in charge asymmetry

- exploring BSM models (later LHC phase)
  $\longrightarrow$ determine masses & spins

consider invariant jet-mass distributions in decay chains like

$$pp \to \tilde{g} + \tilde{g} \to q\tilde{q}_R + q\tilde{q}_L \to qq\tilde{\chi}_1^0 + qq\tilde{\chi}_2^0$$



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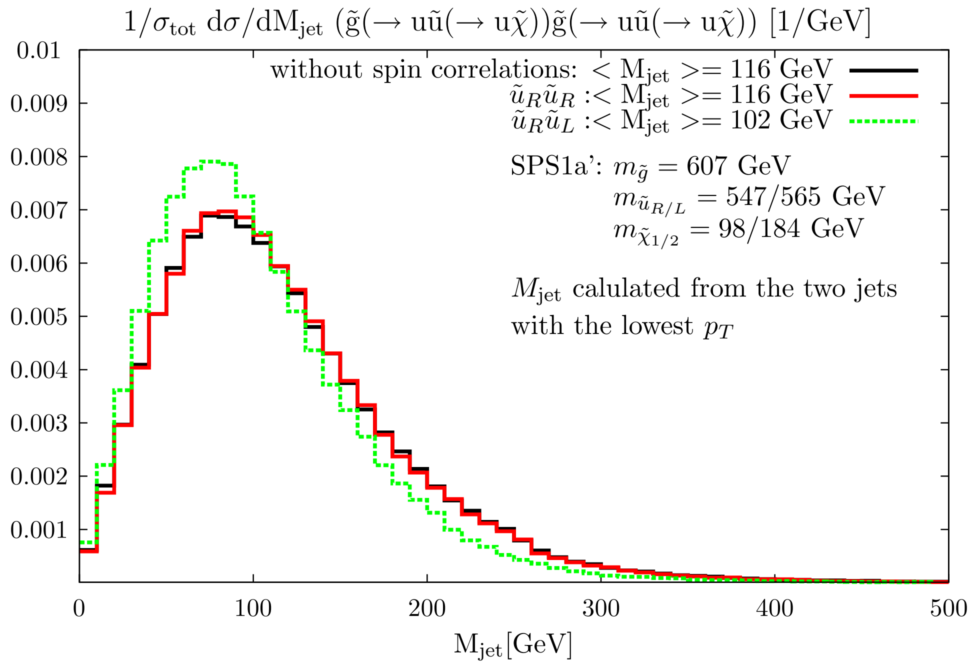

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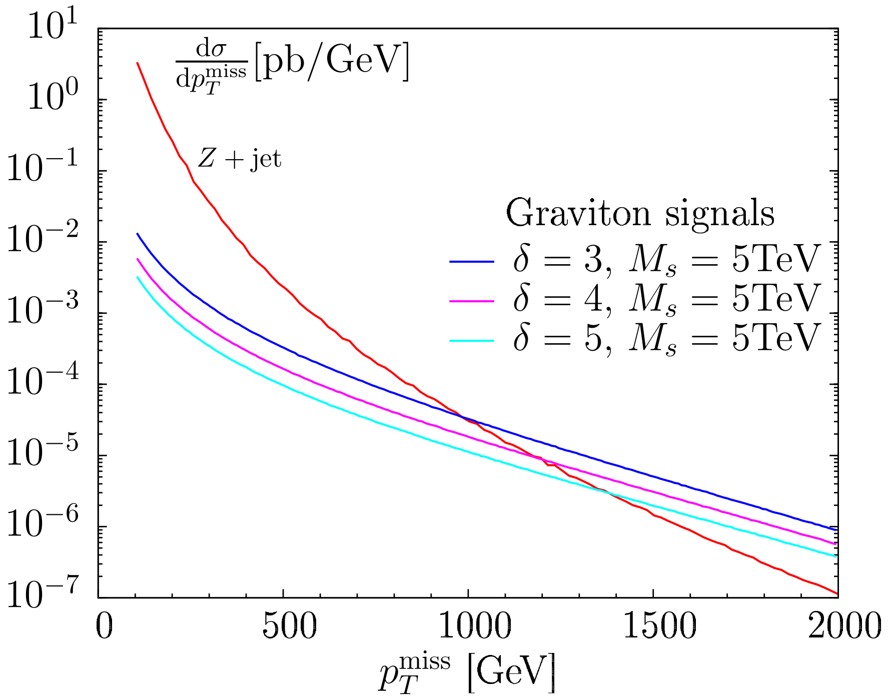
Precision calculations for BSM physics at the LHC

- exploring BSM models (later LHC phase)

  $\longrightarrow$ determine masses & spins . . . or the number of extra dimensions?

consider graviton production in ADD scenarios (Arkani-Hamed, Dimopoulos, Dvali)

$$pp \longrightarrow G + \text{jet} \longrightarrow \text{monojet signature}$$



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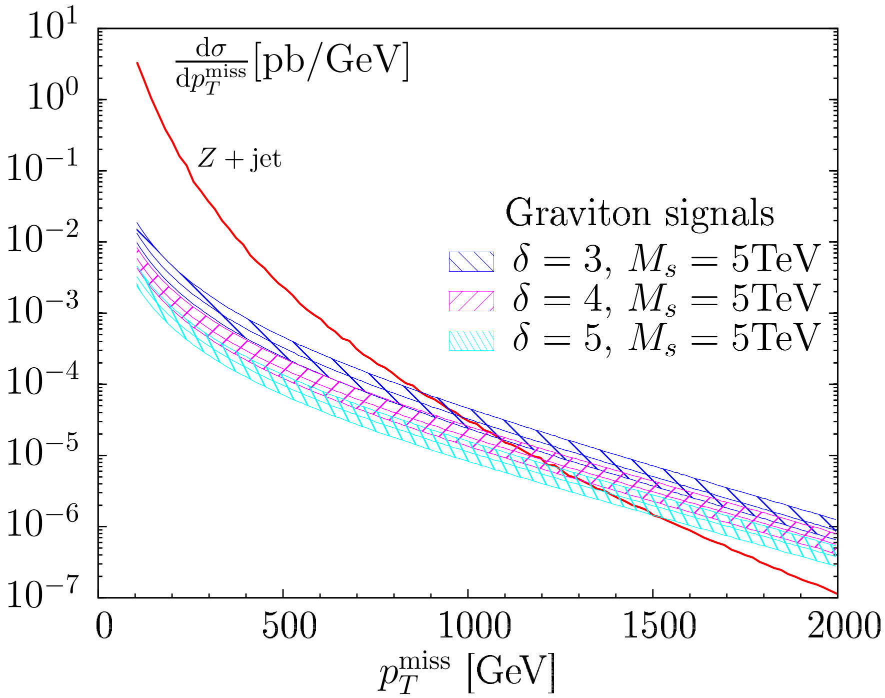

$\longrightarrow$ spoiled by QCD uncertainties. . .

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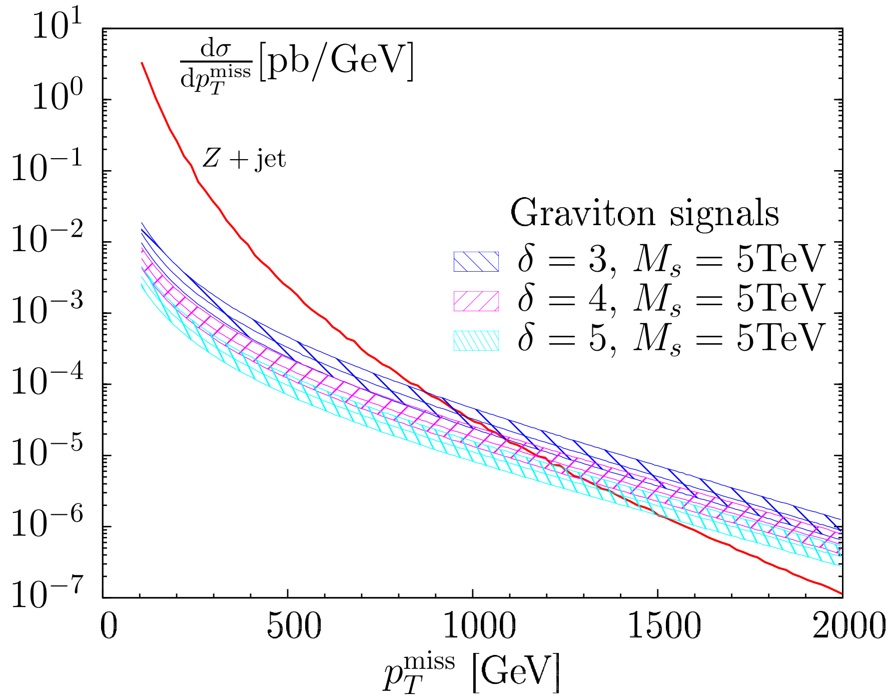

$\longrightarrow$ include NLO-QCD corrections (Karg, MK, Li, Zeppenfeld, in progress)

Progress in SUSY precision calculations at the LHC

- Sparticle production cross sections
  - NLO QCD $\longrightarrow$ Prospino: Beenakker, Höpker, MK, Plehn, Spira, Zerwas
    (cf. Baer, Hall, Reno; Berger, Klasen, Tait)
  - threshold summation for $M_{\tilde{q}}, M_{\tilde{g}} \gtrsim 1$ TeV
    (Bozzi, Fuks, Klasen; Kulesza, Motyka; Langenfeld, Moch;
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  - electroweak corrections
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- Sparticle production $\oplus$ decay: generic BSM cascades (SUSY, UEDs, LH,...)
  - so far only tree level $\longrightarrow$ challenge for LHC theory community...

Precision calculations at the LHC: conclusions & outlook . . .

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  - theoretical uncertainty $\approx 15\%$ for inclusive cross sections
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- First LHC data will allow us to focus on the relevant processes. . .