

La fisica oltre High-Luminosity LHC

Piani e prospettive per future acceleratori



Sommario

F. Bedeschi

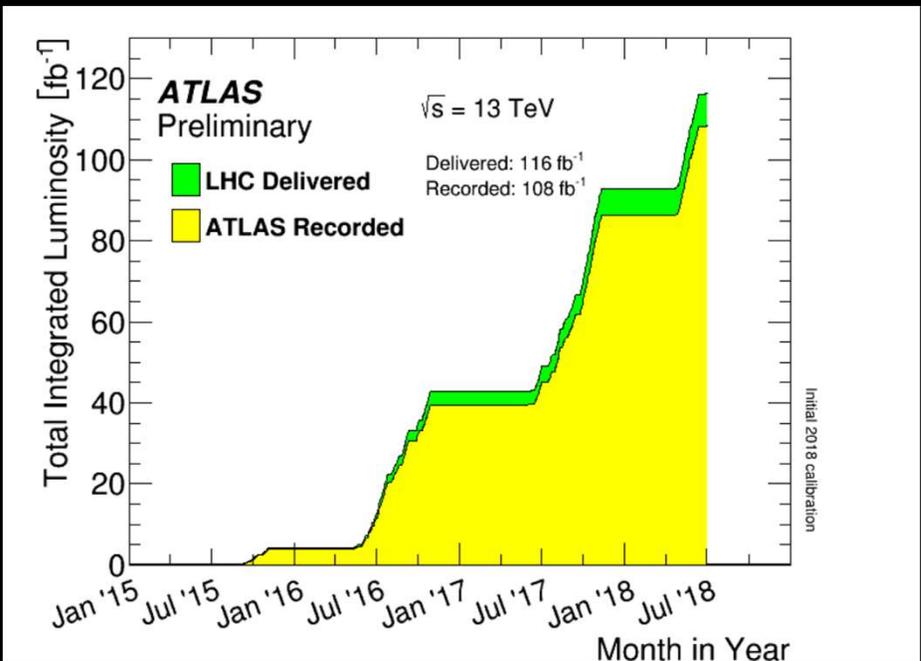
INFN Town Meeting

Roma, Settembre 2018

- ❖ Dove siamo e dove ci porta HL-LHC
- ❖ Scenari possibili dopo HL-LHC
- ❖ Commenti per discussione

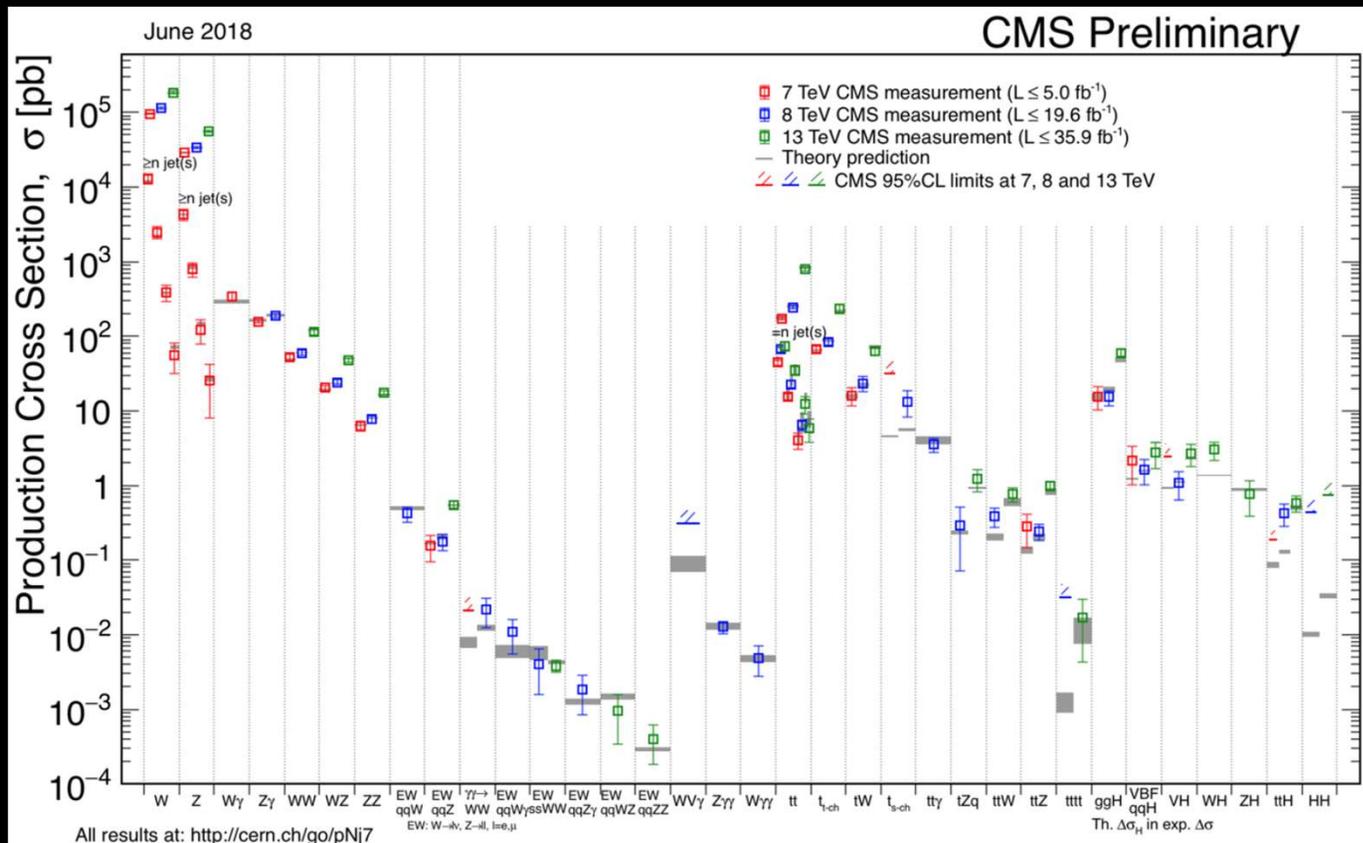
Dove siamo con LHC (1)

❖ $120 \text{ fb}^{-1} \rightarrow \sim 150 \text{ fb}^{-1}$



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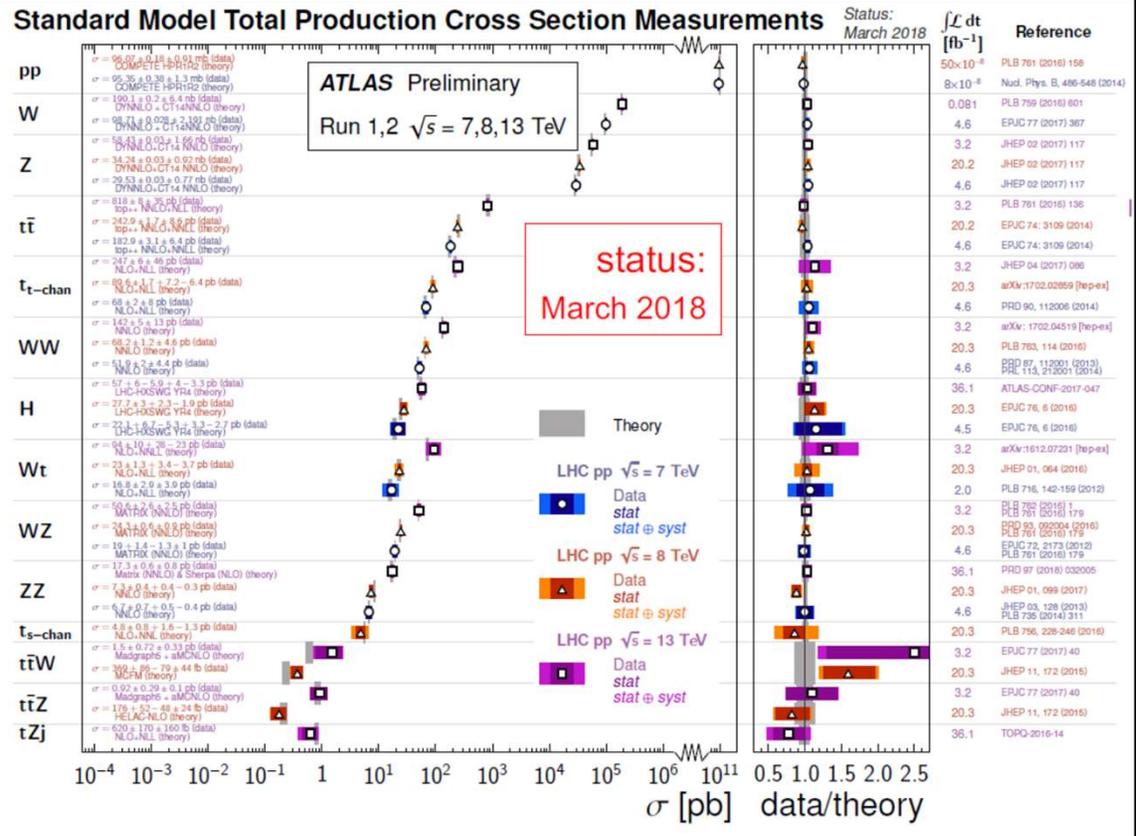
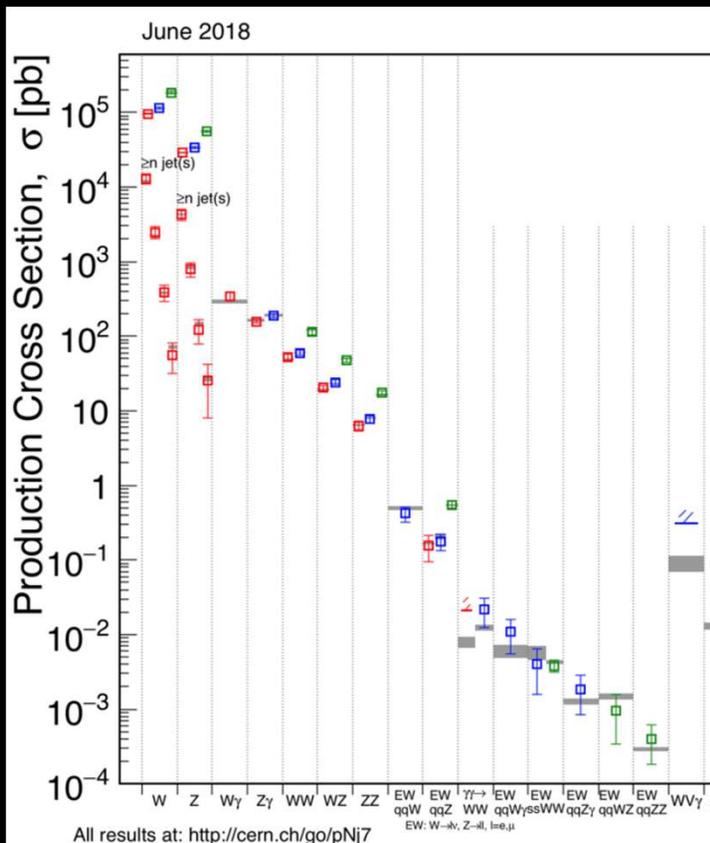
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Dove siamo con LHC (2)

Higgs – oltre la scoperta:

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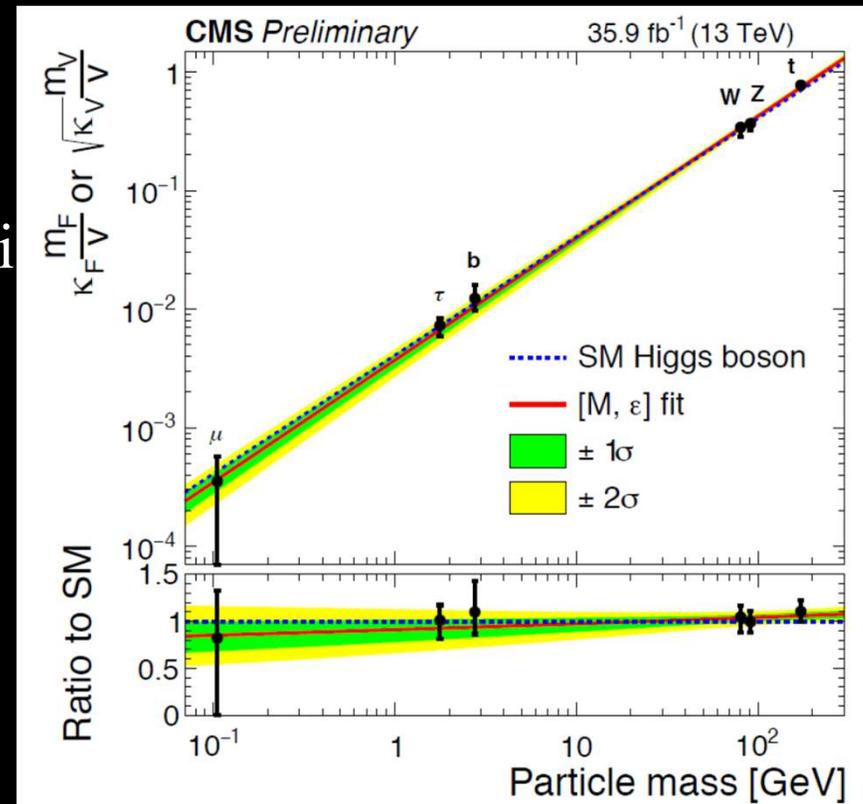
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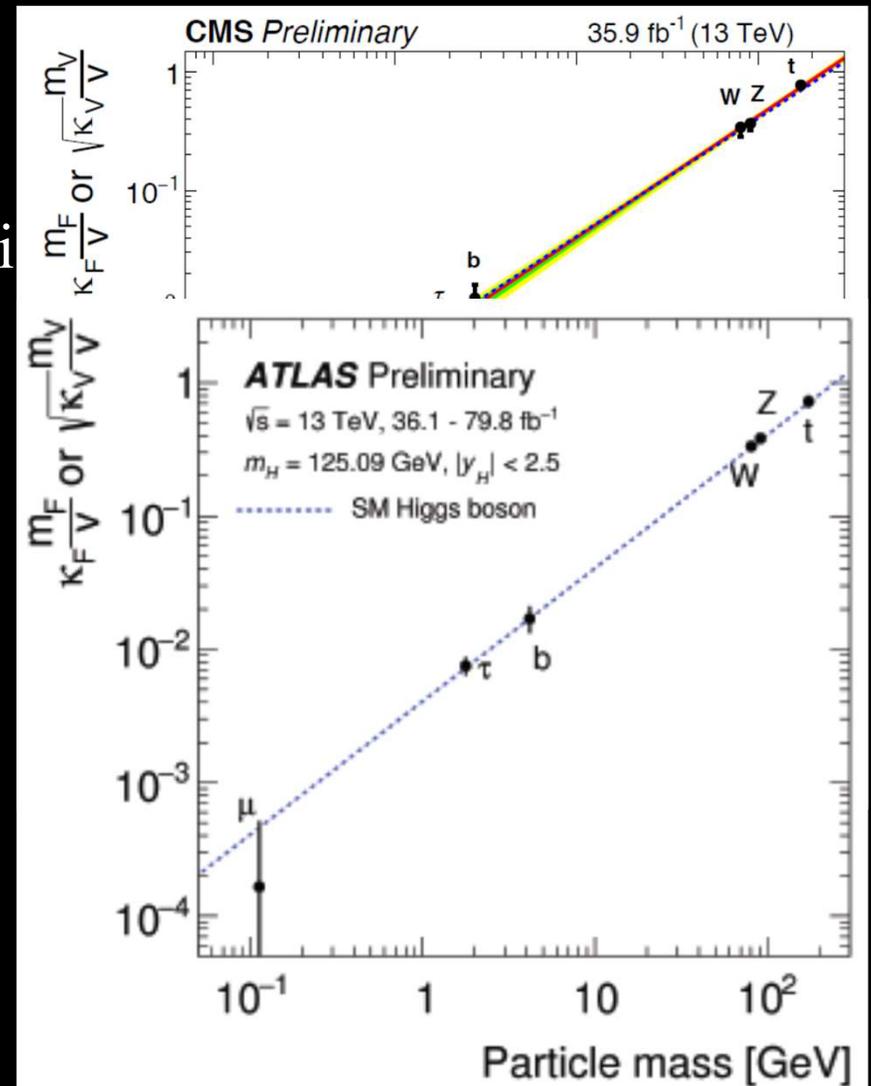
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 - Recentemente $t\bar{t}H$, $\tau^+\tau^-$, b



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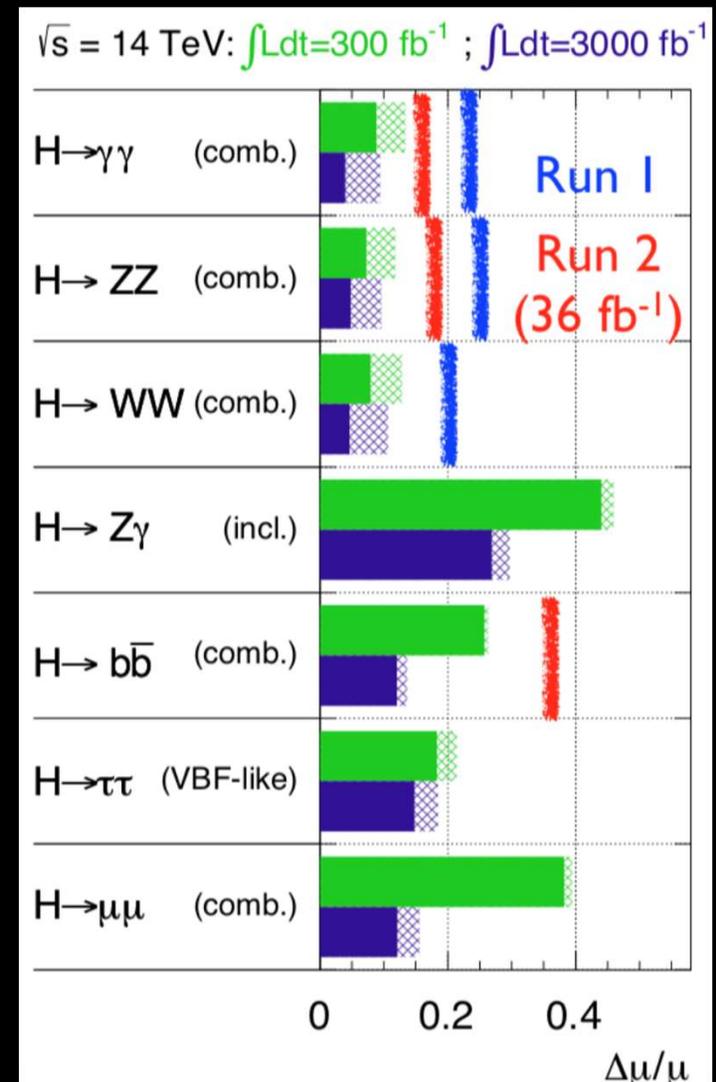
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- Misure couplings $\sim 10\%$ Run 3
 - 5% con HL-LHC
 - Notare il sistematico



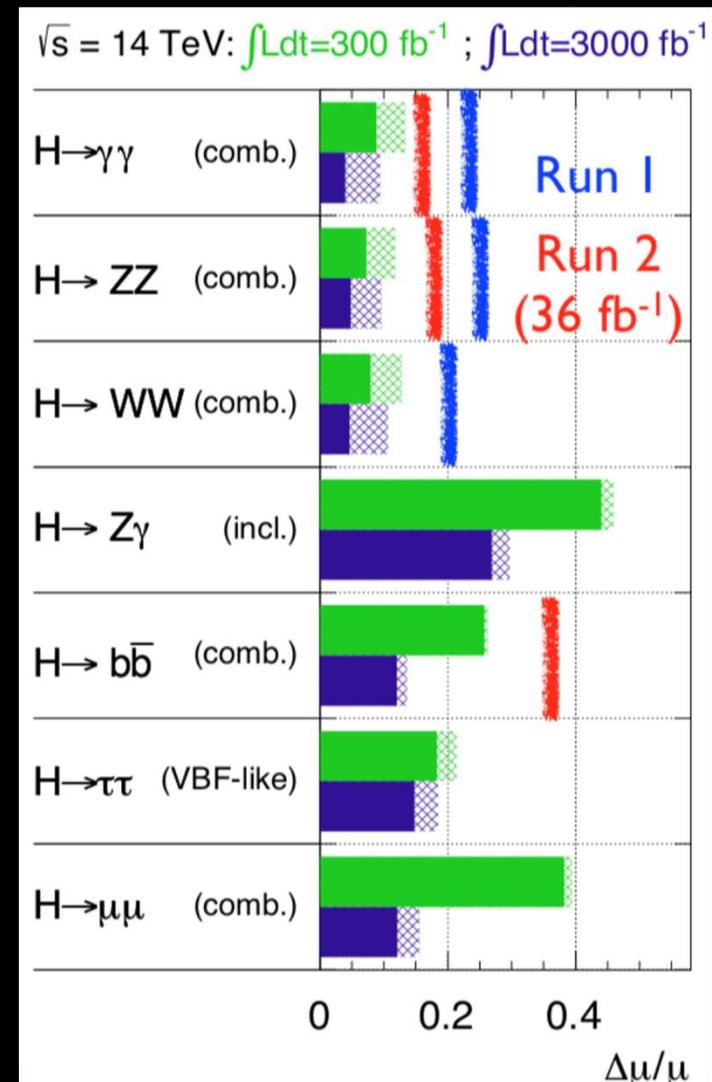
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❖ Deviazione da SM: $\delta \sim v^2/M^2$

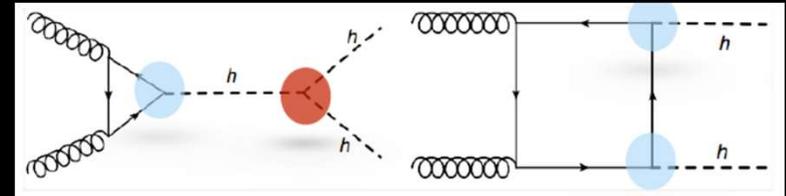
- $v = 246$ GeV, M scala di NP
- $M \sim 1-10$ TeV $\rightarrow \delta \sim 5-0.05\%$
- Serve risoluzione $< \%$



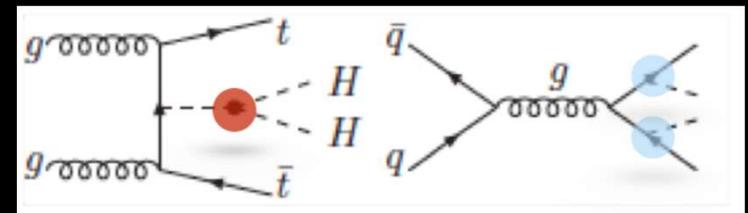
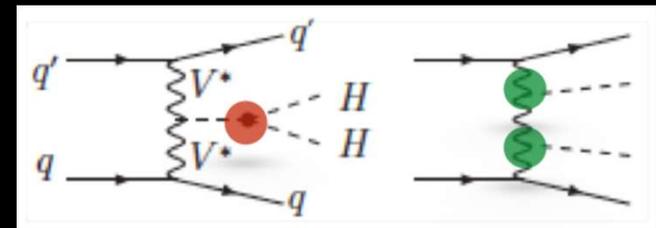
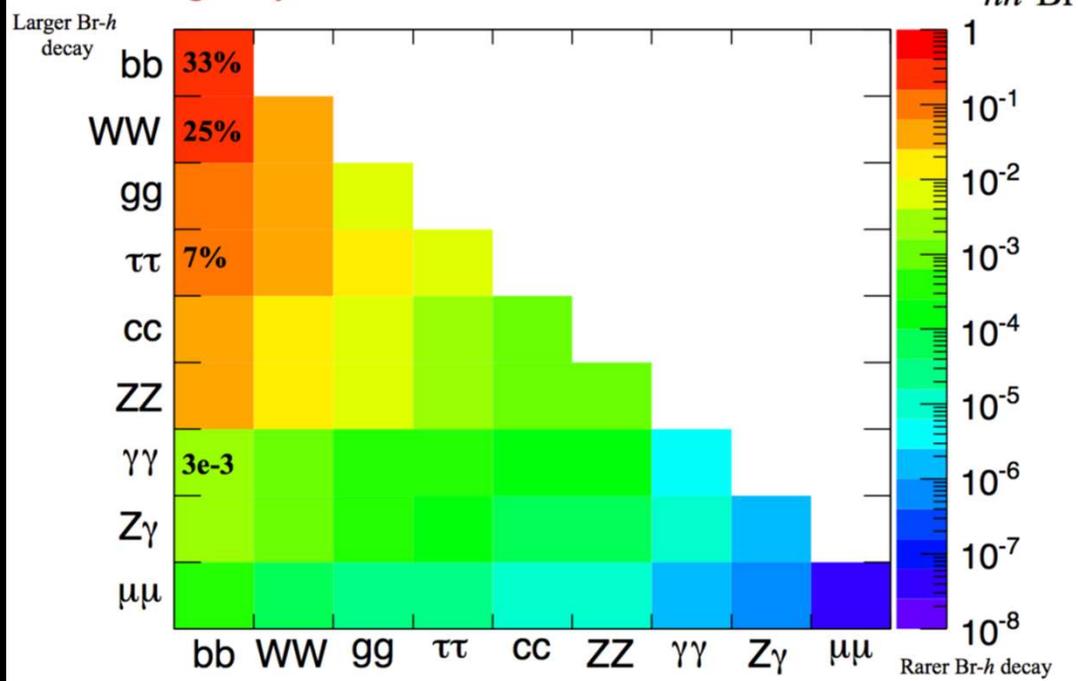
Dove siamo con LHC (3)

❖ Higgs self-coupling difficile

- Interferisce con altri modi
- Bassa x-sec x BR



phenomenologically rich set of final states.



Dove siamo con LHC (3)

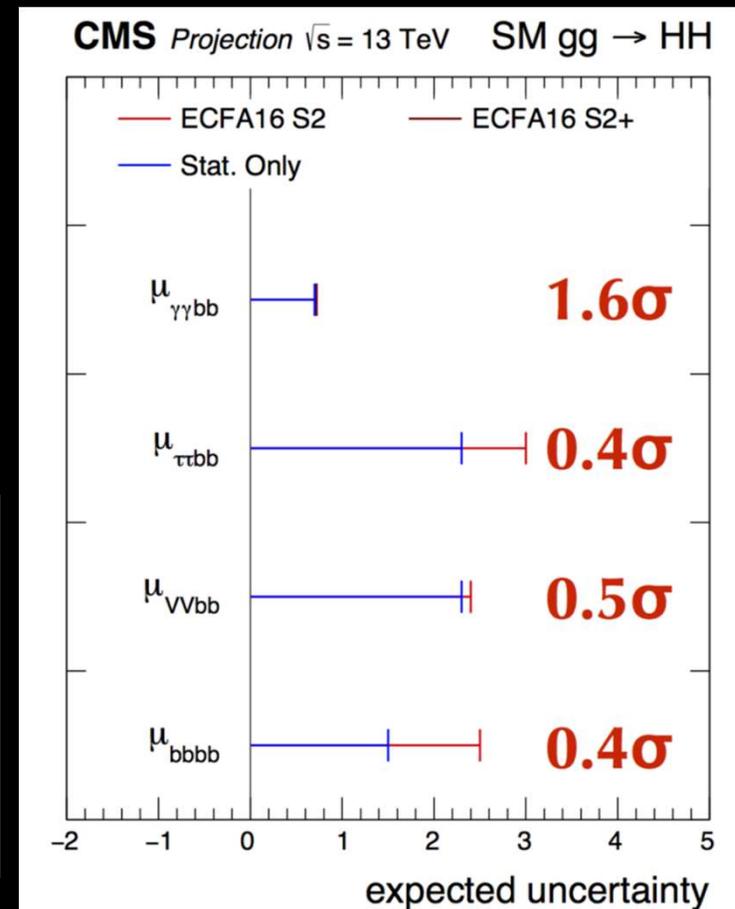
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❖ Proiezioni per HL-LHC

- Combinazione ~ 40-50%

	$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}} @95\%CL$	
$bb\gamma\gamma_{w/o\ sys}$	[-0.8, 7.7]	ATL-PHYS-PUB-2017-001
$bb\tau\tau$	[-4.0, 12.0]	ATL-PHYS-PUB-2015-046
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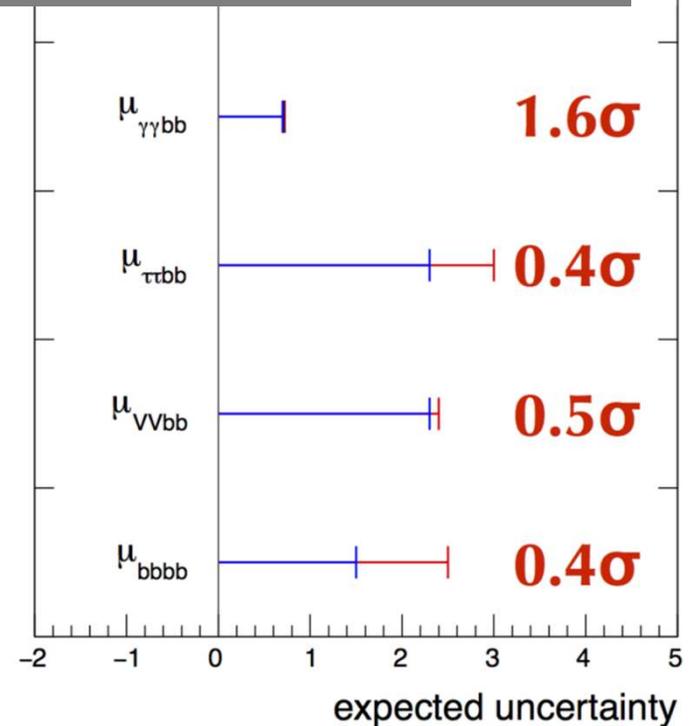
❖ Proiezioni per HL-LHC

- Combinazione \sim 40-50%

❖ NP range: few – 20%

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	-18 %
Composite Higgs	tens of %
Minimal Supersymmetry	-2 % ^a -15 % ^b
NMSSM	-25 %

Gupta et al., arXiv: 1305.6497



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(da conclusioni ICHEP2018)

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➤ Niente SUSY

SUSY particle	Approximate excluded mass (TeV) - Model class	
	Favorable	Challenging
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squark	1.5	0.5
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<i>examples</i>	Mass Lower limit
String resonance (jj)	~ 8 TeV
Excited quark (jj)	~ 6 TeV
Z' (SSM) (ll)	~ 4.5 TeV
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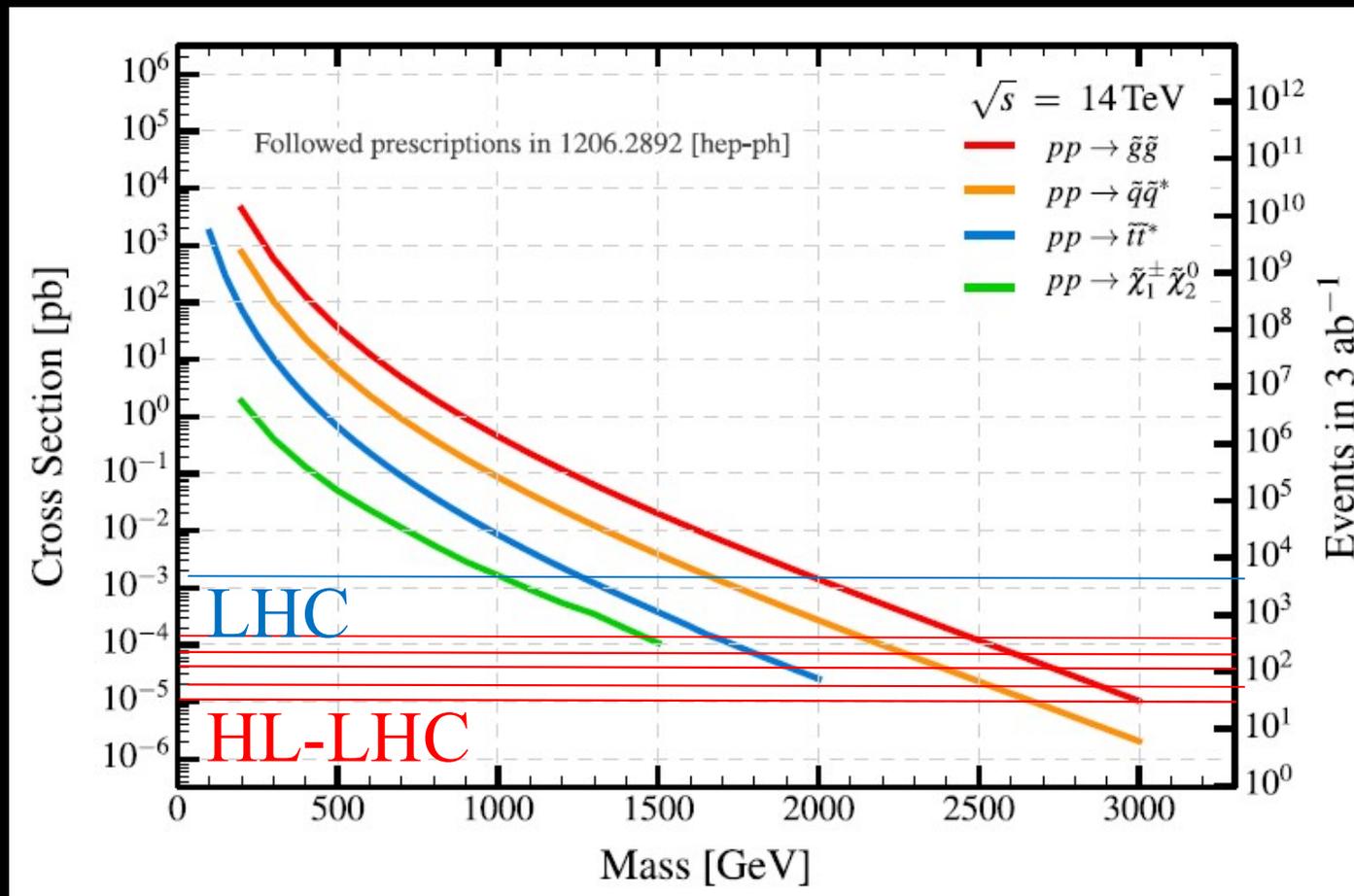
❖ Scala nuova fisica $> \text{TeV}$

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Dove siamo con LHC (4)

❖ Ricerche dirette a HL-LHC alzeranno questi limiti



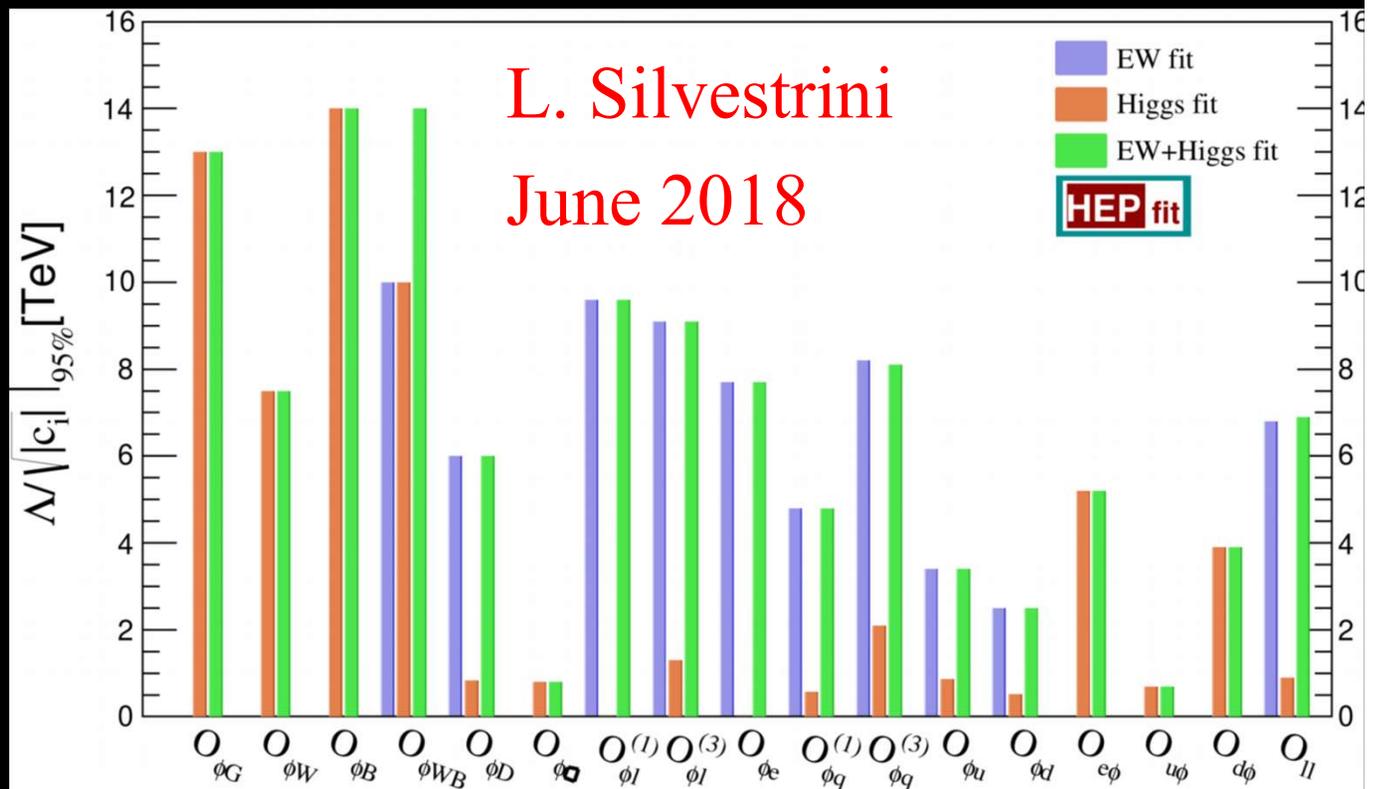
Dove stiamo con LHC (5)

❖ Ricerche indirette con EFT

$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda^2} \sum_k c_k^{(6)} Q_k^{(6)} + \cancel{\frac{1}{\Lambda^4} \sum_k c_k^{(8)} Q_k^{(8)}} + \dots$$

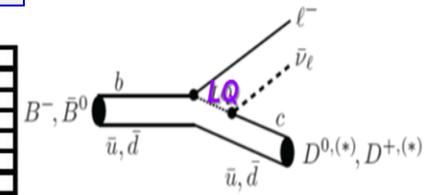
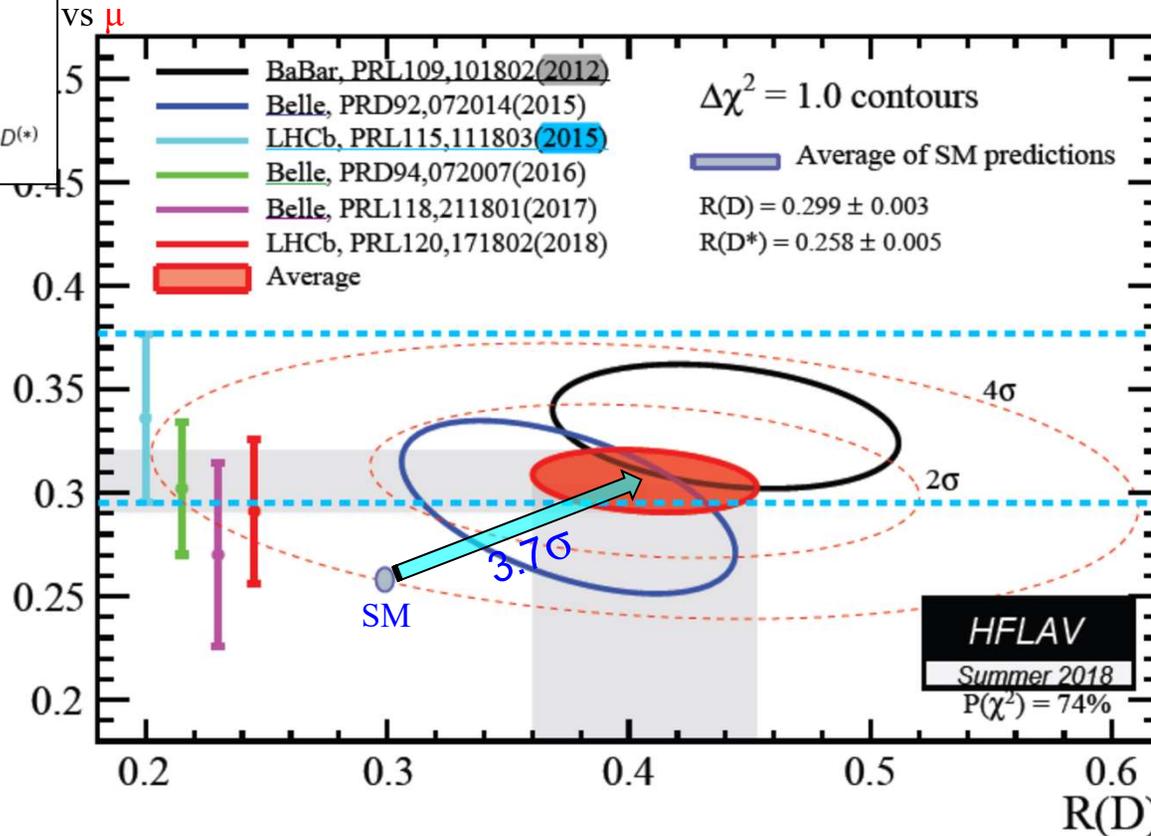
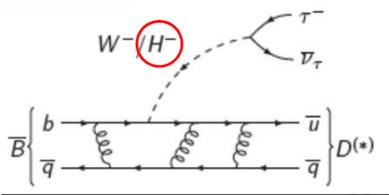
➤ EW > Higgs

■ LEP > LHC





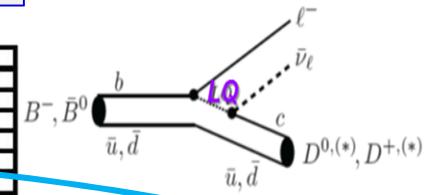
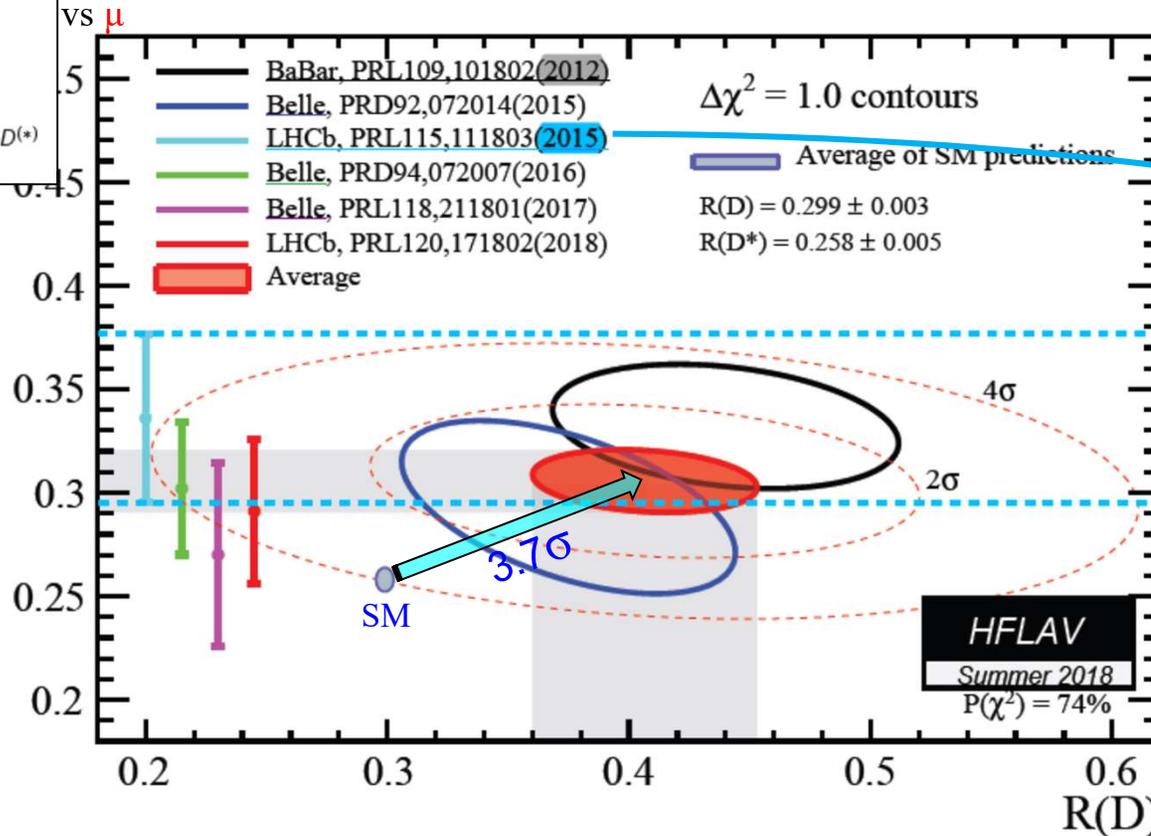
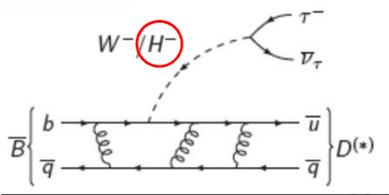
Is $R(D^*)$, $R(D)$ Anomaly Real?



- Two ellipses are $R_D - R_{D^*}$ measurements of BaBar'12 and Belle'15
- R_{D^*} measurement of **LHCb'15** (concur with BaBar) caused sensation



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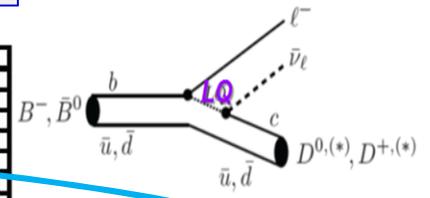
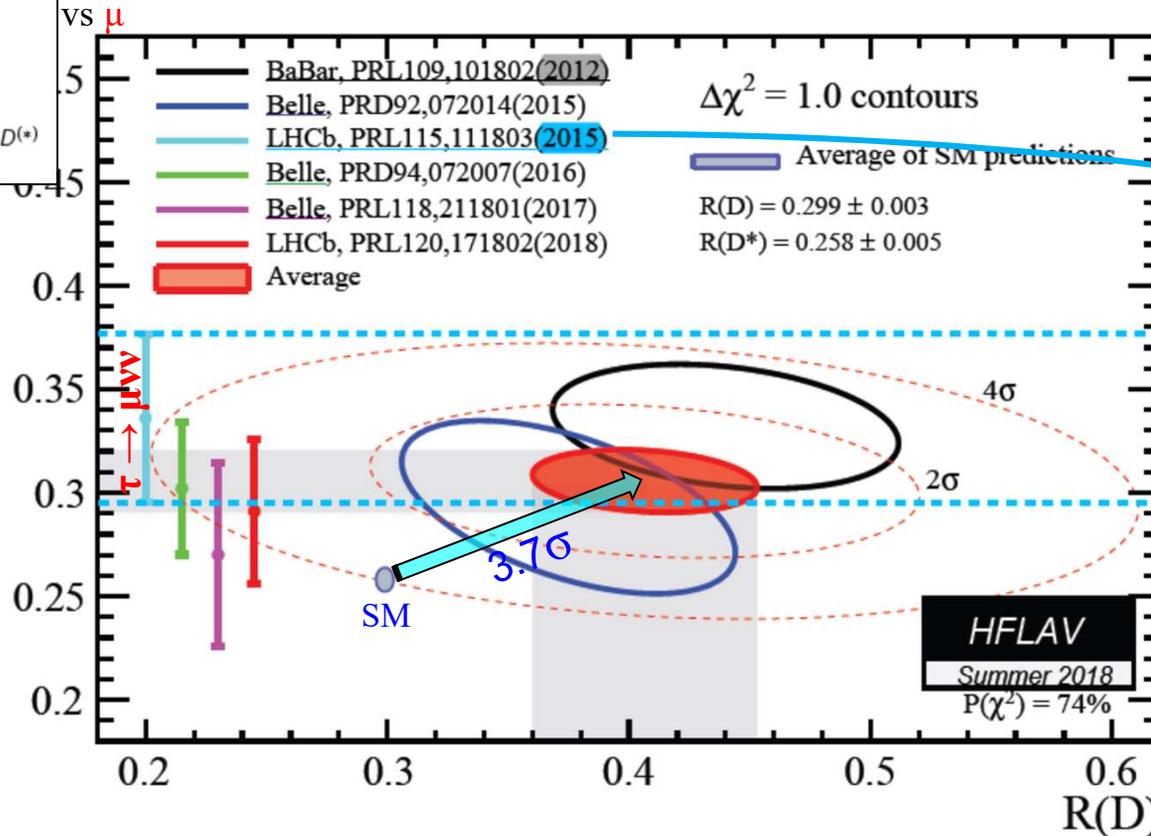
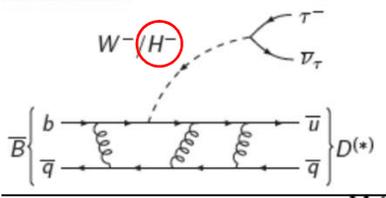


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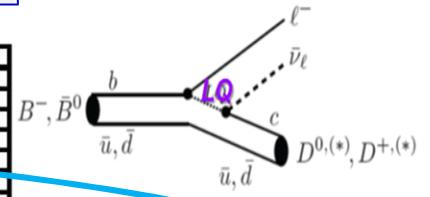
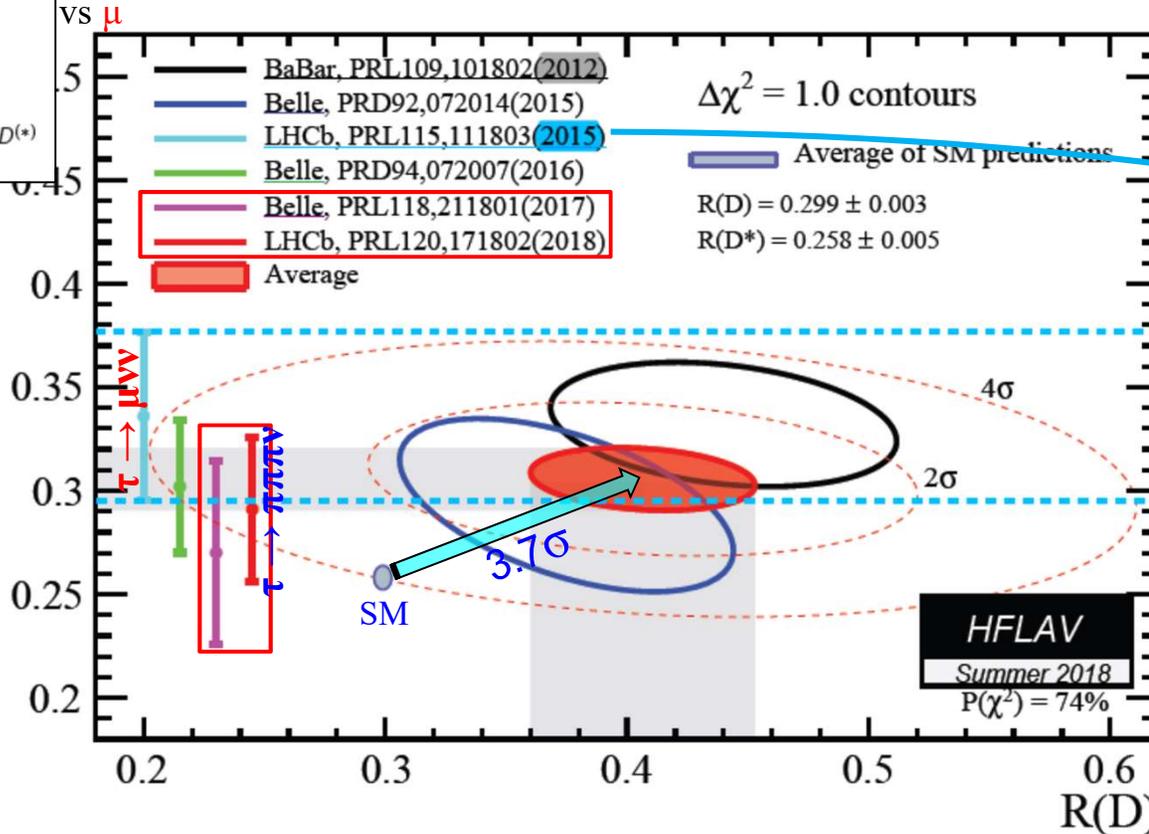
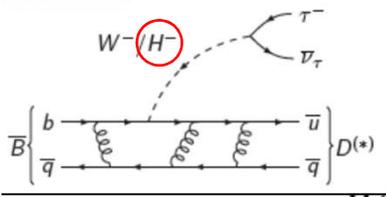


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- Sobering: R_{D^*} measurement of **LHCb'18 consistent w/ SM** (via $\tau \rightarrow 3\text{-prong}$)
 R_{D^*} – and $\tau_{\text{pol.}}$ – measurement by **Belle'18 ~ SM**

LHC: Bottom line

❖ Tante bellissime misure che confermano lo SM

- Incluso miglioramenti su parametri importanti come M_{top} , M_W e $\sin(\theta_W)$ – NB. Serie limitazioni da sistematica

❖ Ricerche dirette e indirette di nuova fisica non trovano nessuna indicazione chiara

- Scala nuova fisica punta oltre il TeV
- HL aumenta il reach in massa di un fattore ~ 1.5 per SUSY

❖ Higgs:

- Precisione su couplings non permette di esplorare zona $> \text{TeV}$ anche con HL
- Doppio Higgs osservato ma con grandi errori a HL

Non proprio secondo le attese!

Many of our past expectations have been shattered
Naturalness as guiding principle

G. Giudice, FCC meeting, Rome 2016

Technicolor → no fundamental Higgs

Supersymmetry → $m_h \lesssim 120$ GeV,
 $\tilde{m}_t \lesssim 300$ GeV, $\tilde{m}_g \lesssim 1$ TeV

Extra dimensions → hell breaks loose at TeV

Composite Higgs → $\Delta BR_h \sim O(1)$

No!
No!
No!

No!

Change of paradigm?

Che direzione prendere?

❖ “Confusion is the best moment in science”

➤ G. Giudice: FCC week, Rome, April 2016

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❖ the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can *guarantee discoveries* beyond the SM, and *answers to the big questions of the field*:

➤ M. Mangano: 98° ECFA meeting, Nov. 2015

Alcuni criteri guida

❖ Criteri per valutare future infrastrutture (da MLM):

- “Deliverables” garantiti
- Potenziale di esplorazione
 - Di ampi e ben giustificati scenari BSM
- Potenziale per dare risposte conclusive a importanti questioni di ampio respiro

❖ Criteri pratici aggiuntivi

- Quando sara’ disponibile la tecnologia necessaria?
- Sono accettabili i costi di costruzione e funzionamento?

Cosa c'e' sul piatto

❖ Costruibile adesso piu' o meno

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- LHeC

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- PWFA = «Plasma WakeField Acceleration»
- Muon collider

Vedi talk di M. Ferrario

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❖ Potenziali estensioni

- ILC/CLIC → PWFA
- CepC/FCC-ee/LHeC → Muon collider

Costruibili adesso ... +/-

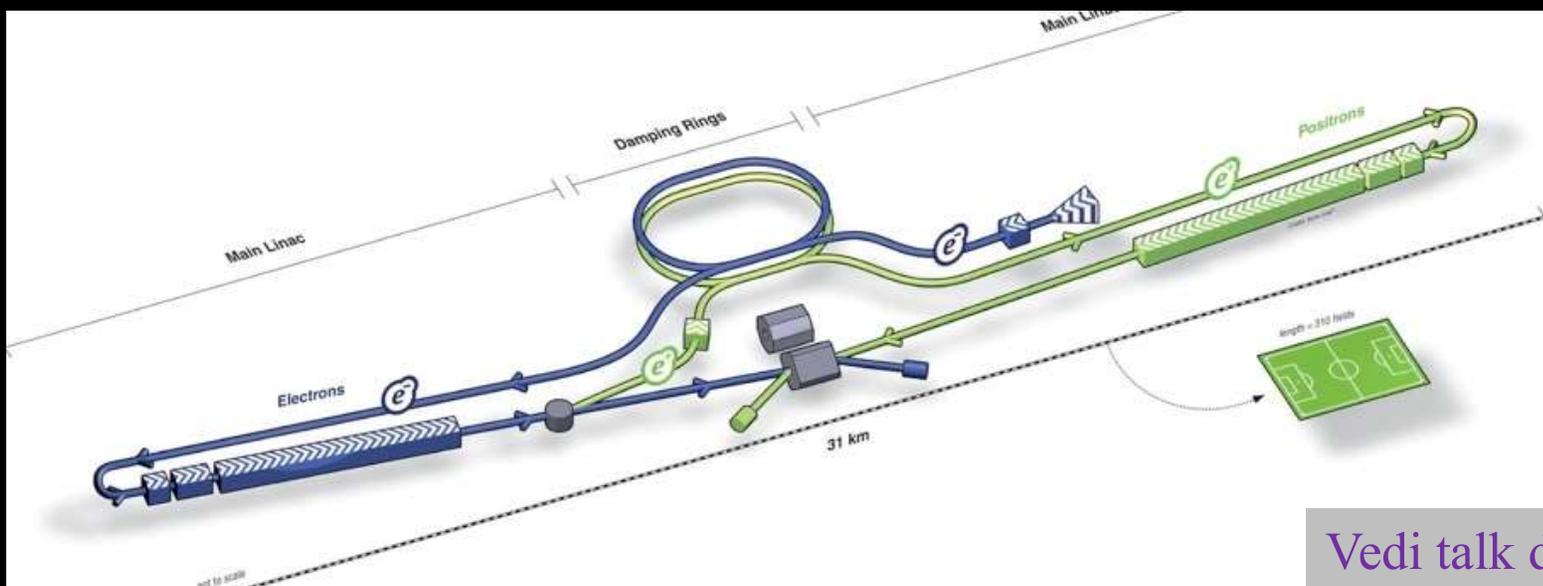
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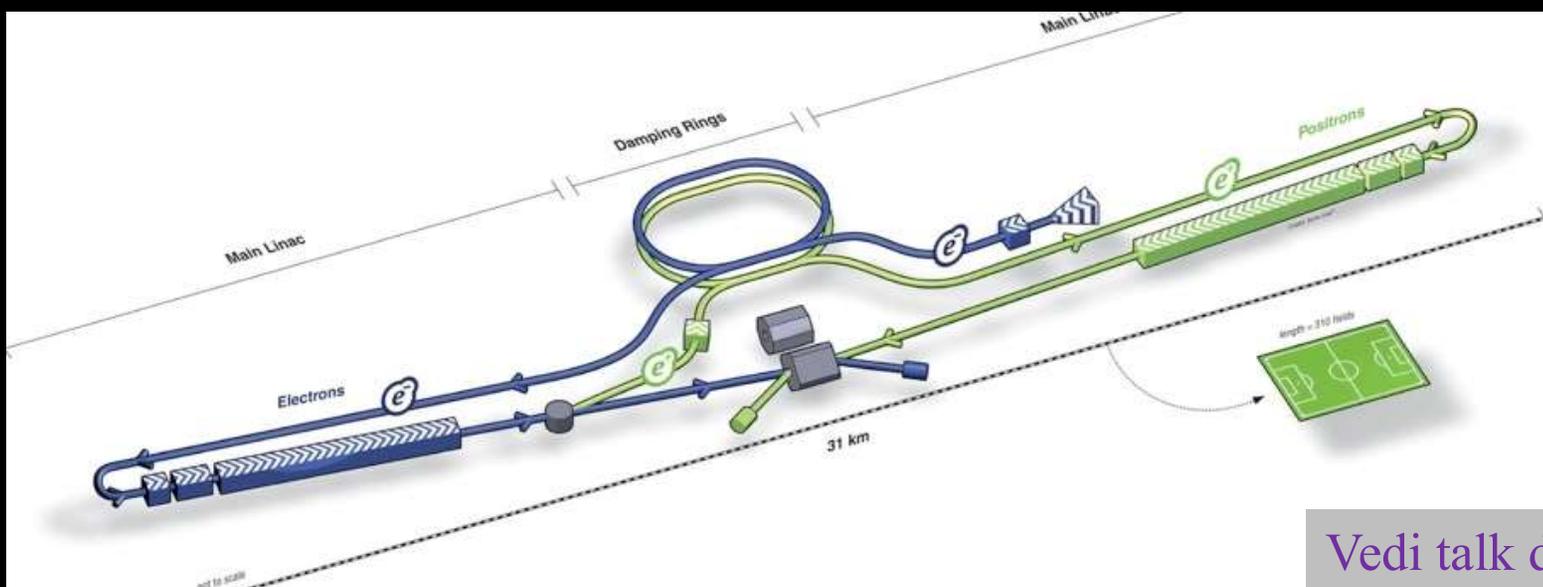


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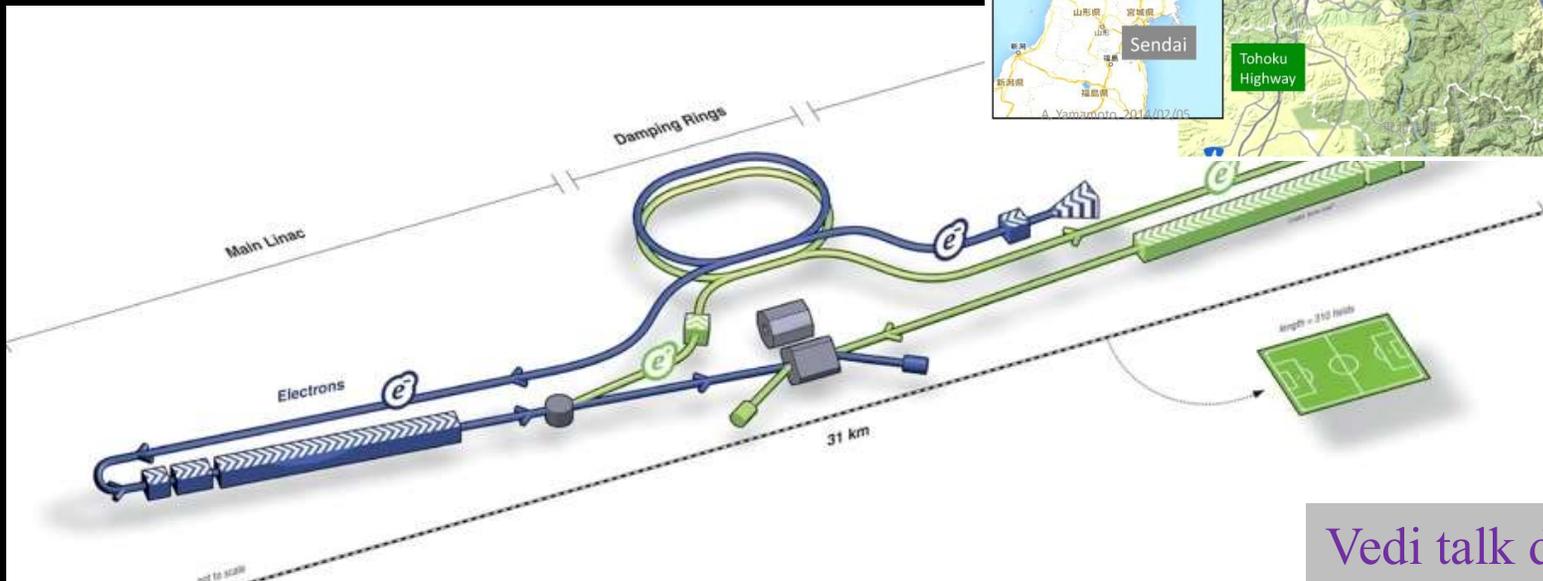
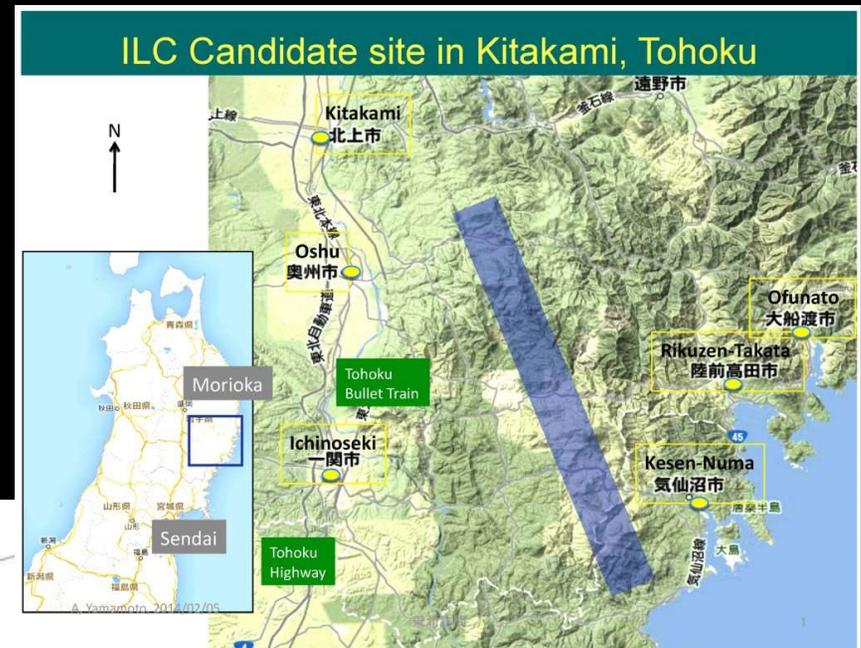


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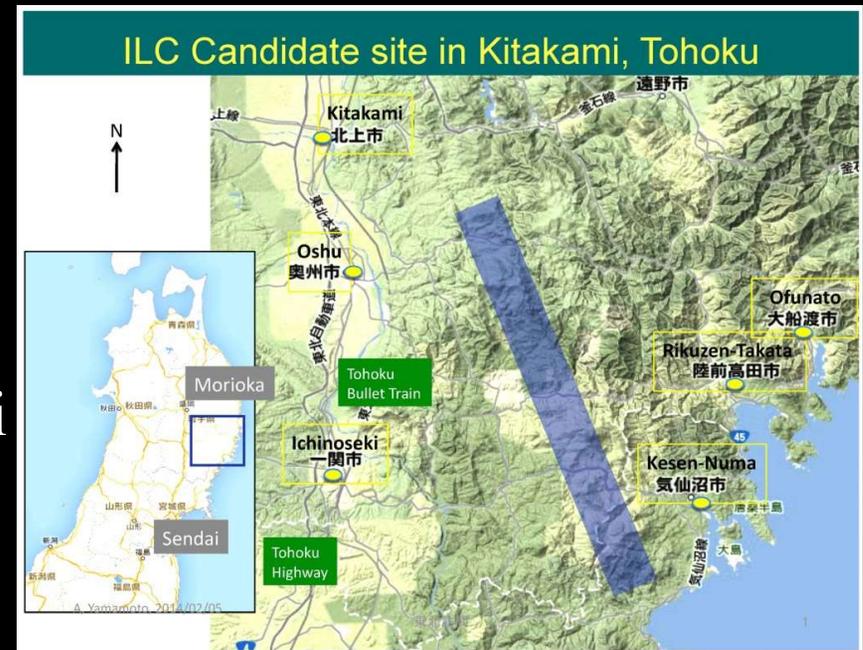


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- Descoping a 250 GeV e ridotti costi
 - Attesa risposta da governo
Giapponese in tempo per ESU

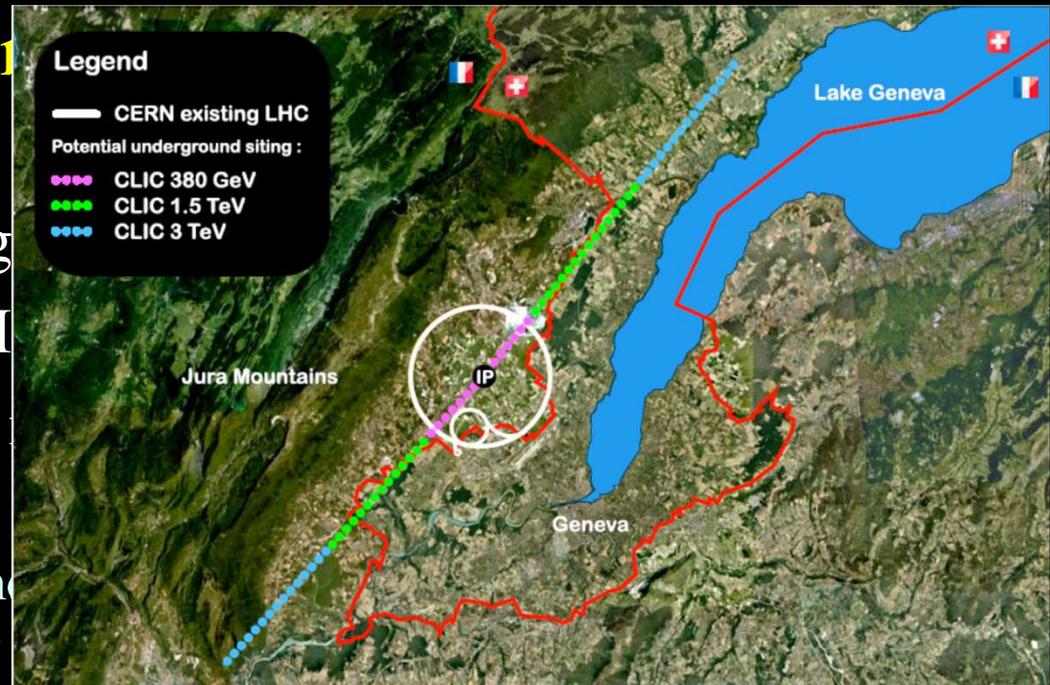


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Costruibili adesso ... +/-

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❖ CLIC: linear e⁺e⁻ collider

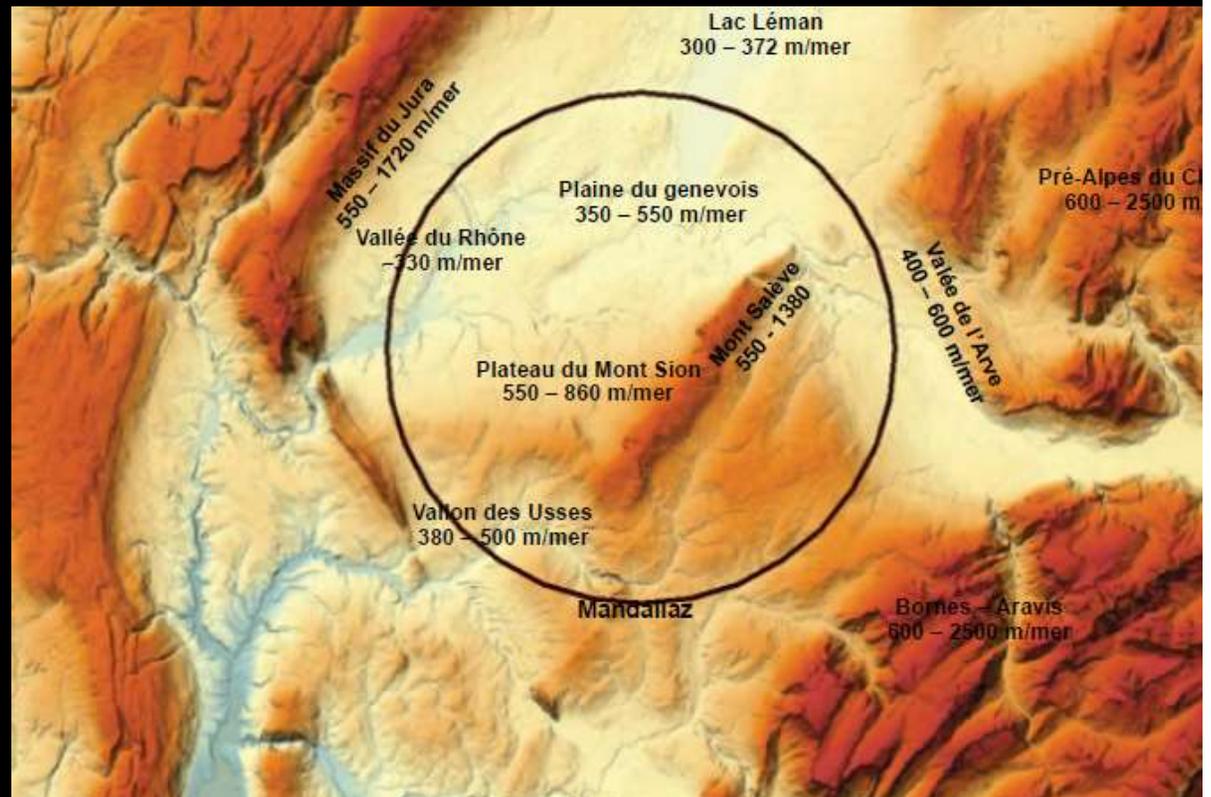
- Staged: 380 GeV to 3 TeV
 - Higgs e top a 380 GeV
 - Tecnologia meno matura

Vedi talk di A. Variola

Costruibili adesso +/-

❖ FCC-ee: circular e⁺e⁻ collider

- ~100 km tunnel
- 90 - 365 GeV
- CDR 2018



Vedi talk di A. Variola

Costruibili adesso +/-



❖ CepC: circular e+e- collider

- 100 km tunnel
- 90 - 250 GeV
- Pre-CDR finished
- CDR 2018

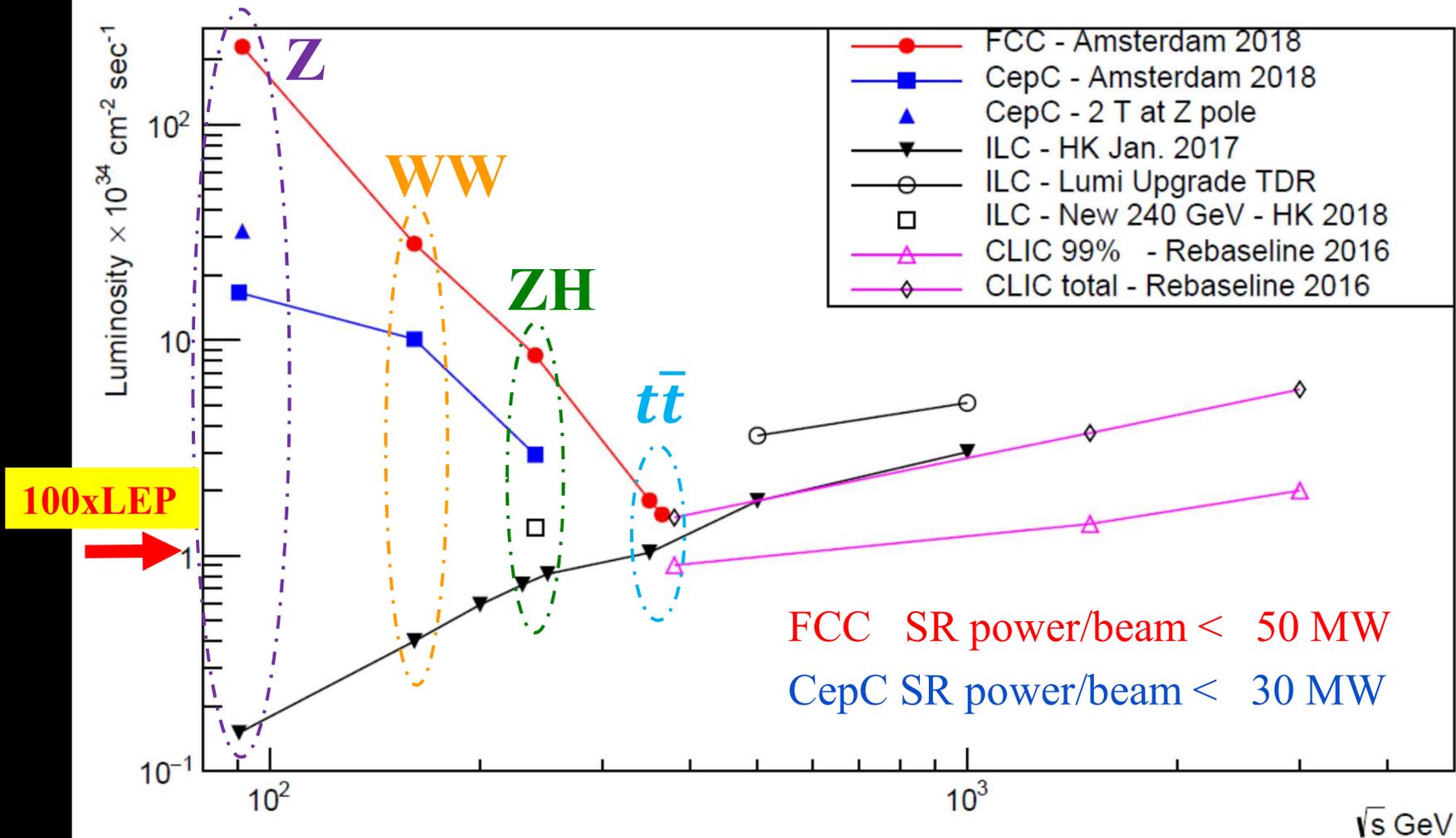
X. Lou, ICHEP,
Seul 2018

Vedi talk di A. Variola

CepC, FCC, ILC, CLIC

luminosity comparison

e^+e^- Collider Luminosities



e^+e^- collider potential (1)

e^+e^- collider potential (1)

	Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
Z	m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
	Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1 *	QED / EW
	R_1	Peak	20.767 ± 0.025	0.001	< 0.001	Statistics
	R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \rightarrow bb$
	N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
	$\sin^2\theta_W^{\text{eff}}$	$A_{\text{FB}}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	0.000003	< 0.000005 *	Beam energy
	$1/\alpha_{\text{QED}}(m_Z)$	$A_{\text{FB}}^{\mu\mu}$ (off-peak)	128.952 ± 0.014	0.004	< 0.004	QED / EW
	$\alpha_s(m_Z)$	R_1	0.1196 ± 0.0030	0.00001	< 0.0002	New Physics
W	m_W (MeV)	Threshold scan	80385 ± 15	0.6	< 0.6	EW Corr.
	Γ_W (MeV)	Threshold scan	2085 ± 42	1.5	< 1.5	EW Corr.
	N_ν	$e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, ll$	2.92 ± 0.05	0.001	< 0.001	?
	$\alpha_s(m_W)$	$B_{\text{had}} = (\Gamma_{\text{had}}/\Gamma_{\text{tot}})_W$	$B_{\text{had}} = 67.41 \pm 0.27$	0.00018	< 0.0001	CKM Matrix
t	m_{top} (MeV)	Threshold scan	$173340 \pm 760 \pm 500$	20	< 40	QCD corr.
	Γ_{top} (MeV)	Threshold scan	?	40	< 40	QCD corr.
	λ_{top}	Threshold scan	$\mu = 1.2 \pm 0.3$	0.08	< 0.05	QCD corr.
	ttZ couplings	$\sqrt{s} = 365$ GeV	~30%	~2%	< 2%	QCD corr

Courtesy of D. D'Enterria, FCC week 2018, Amsterdam

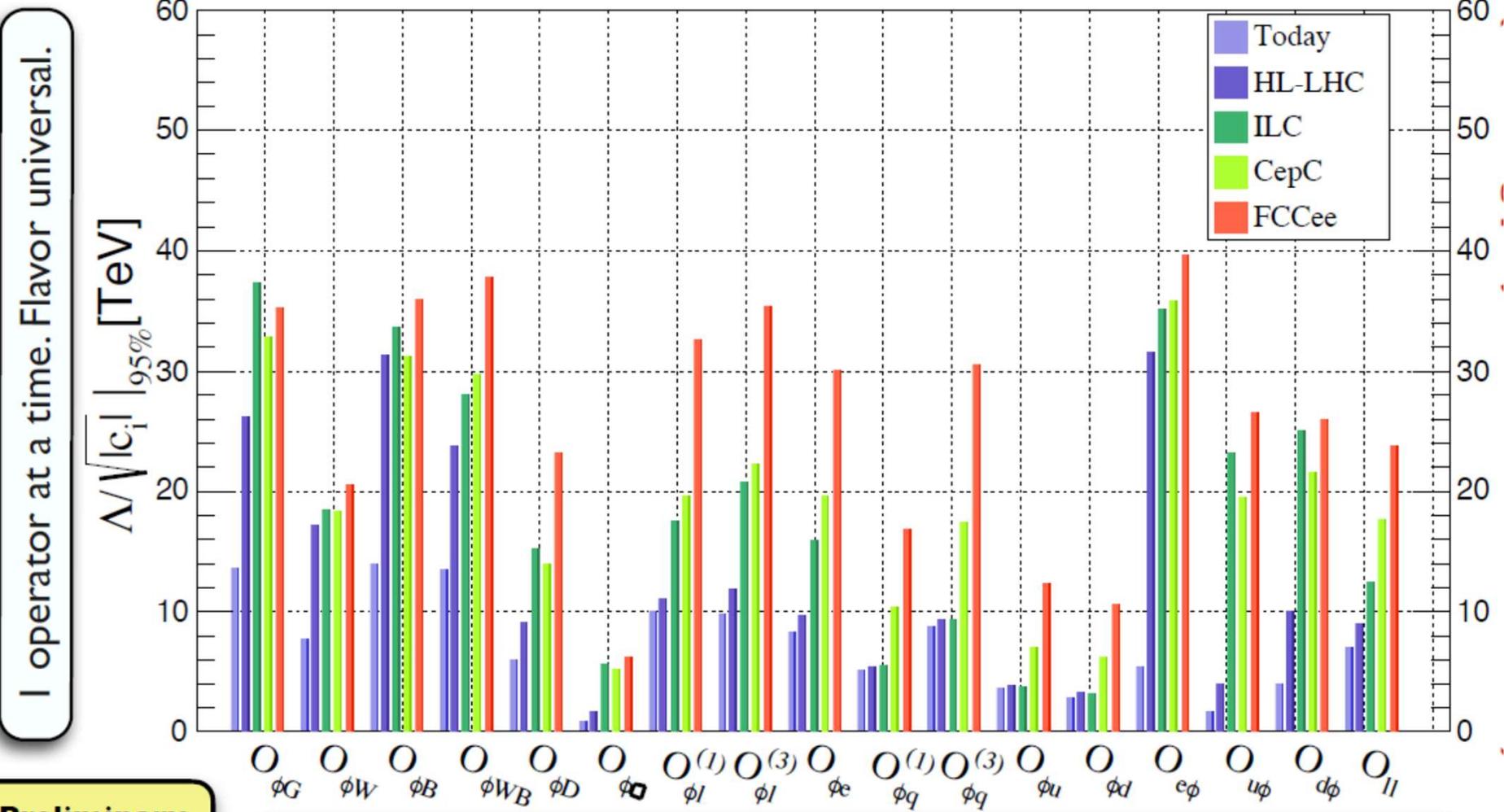
e^+e^- collider potential (1)

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1 *	QED / EW
R_1	Peak	20.767 ± 0.025	0.001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \rightarrow bb$
N_ν	Peak	2.984 ± 0.008	0.000004	< 0.004	Lumi meas
$\sin^2\theta_W^{\text{eff}}$	$A_{\text{FB}}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	0.000003	< 0.000005 *	Beam energy
$1/\alpha_{\text{QED}}(m_Z)$	$A_{\text{FB}}^{\mu\mu}$ (off-peak)	128.953 ± 0.014	0.004	< 0.004	QED / EW
$\alpha_s(m_Z)$	R_1	1196 ± 0.0030	0.00001	< 0.0002	New Physics
m_W (MeV)	Threshold scan	80385 ± 16	0.6	< 0.6	EW Corr.
Γ_W (MeV)	Threshold scan	2075 ± 42	1.5	< 1.5	EW Corr.
N_ν	$e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, \text{II}$	2.982 ± 0.05	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{\text{had}} = (\Gamma_{\text{had}}/\Gamma_{\text{tot}})_{\nu}$	67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	$173340 \pm 760 \pm 500$	20	< 40	QCD corr.
Γ_{top} (MeV)	Threshold scan	?	40	< 40	QCD corr.
λ_{top}	Threshold scan	$\mu = 1.2 \pm 0.3$	0.08	< 0.05	QCD corr.
ttZ coupling	$\sqrt{s} = 365 \text{ GeV}$	$\sim 30\%$	$\sim 2\%$	$< 2\%$	QCD corr

Courtesy of D. D'Enterria, FCC week 2018, Amsterdam

EWPO+HIGGS AT FUT. COLL.: SENSITIVITY TO NP

● Dimension six SMEFT (**EWPD+Higgs**): **Present vs. Future**

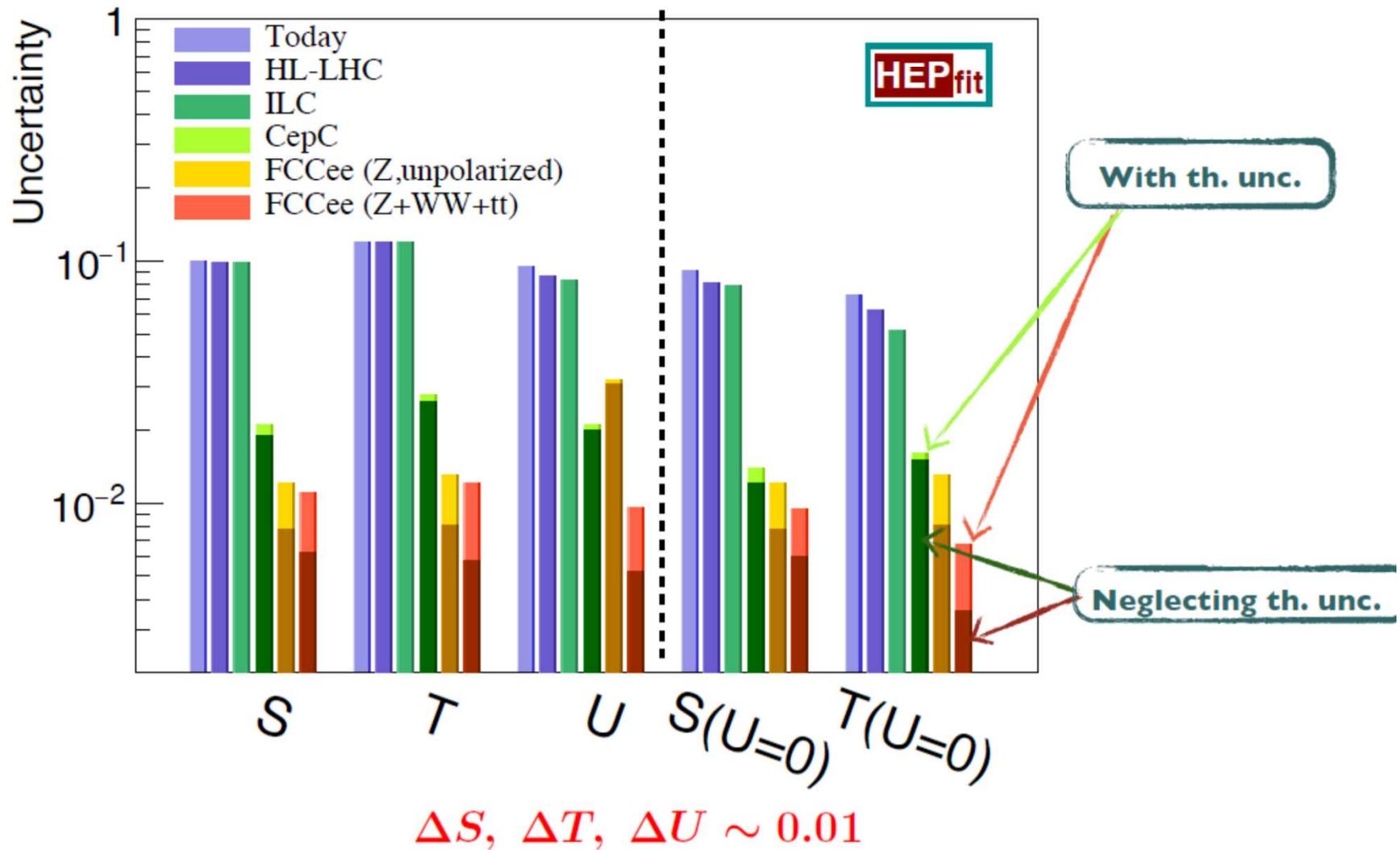


Preliminary

EWPO+Higgs at future colliders: NP interaction scale >5-40 TeV (C_i ~ 1)

EWPO AT FUTURE COLLIDERS: SENSITIVITY TO NP

● Oblique Parameters (S, T, U): Present vs. Future

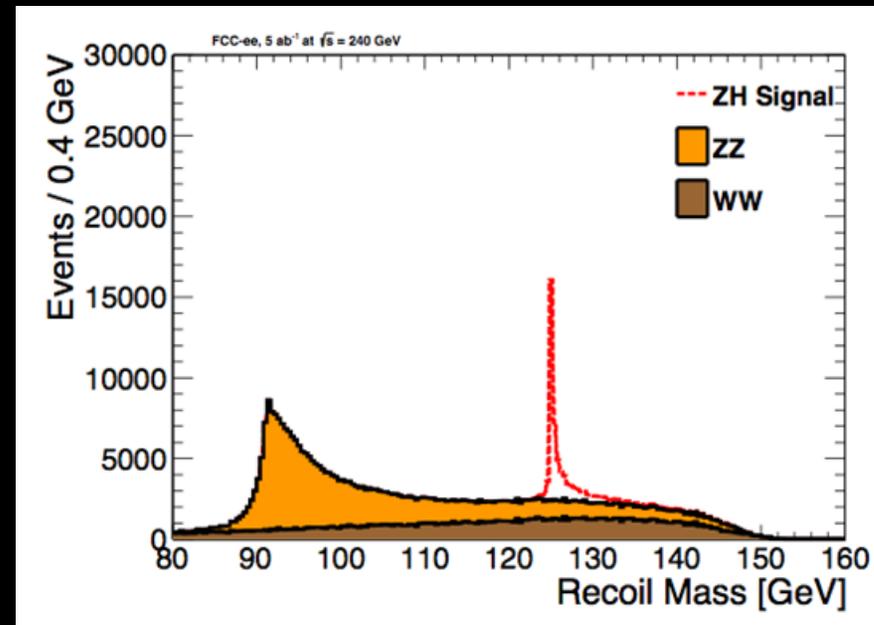
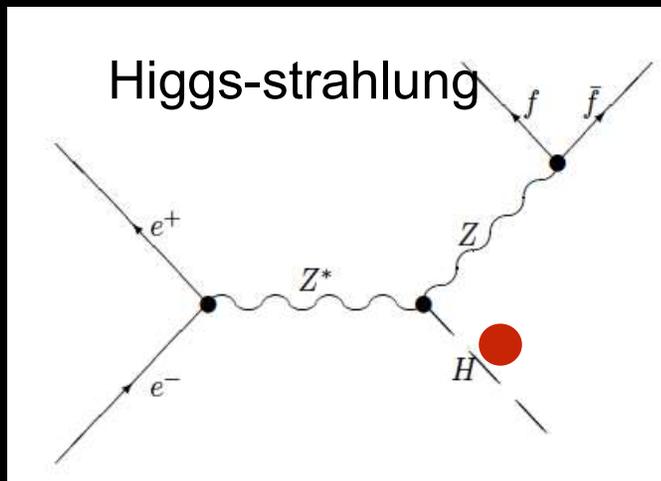


e^+e^- collider potential (2)

❖ ZH: Higgs couplings

- One order of magnitude better than LHC
- ~ No model dependence in BR measurements
- Accessible scale for new physics ~ several TeV

$$\Lambda \gtrsim (1 \text{ TeV}) / \sqrt{(\delta g_{HXX} / g_{HXX}^{\text{SM}}) / 5\%}$$



e^+e^- collider potential (2)

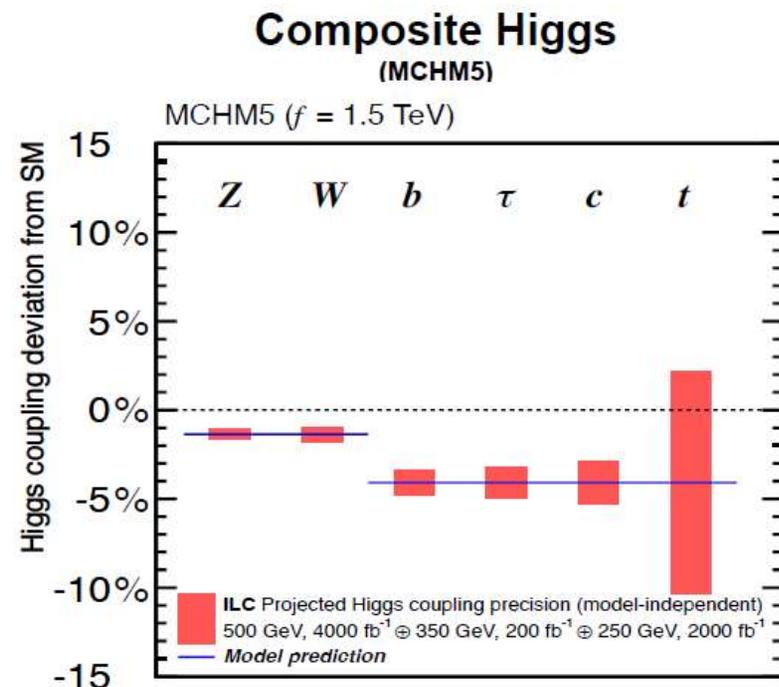
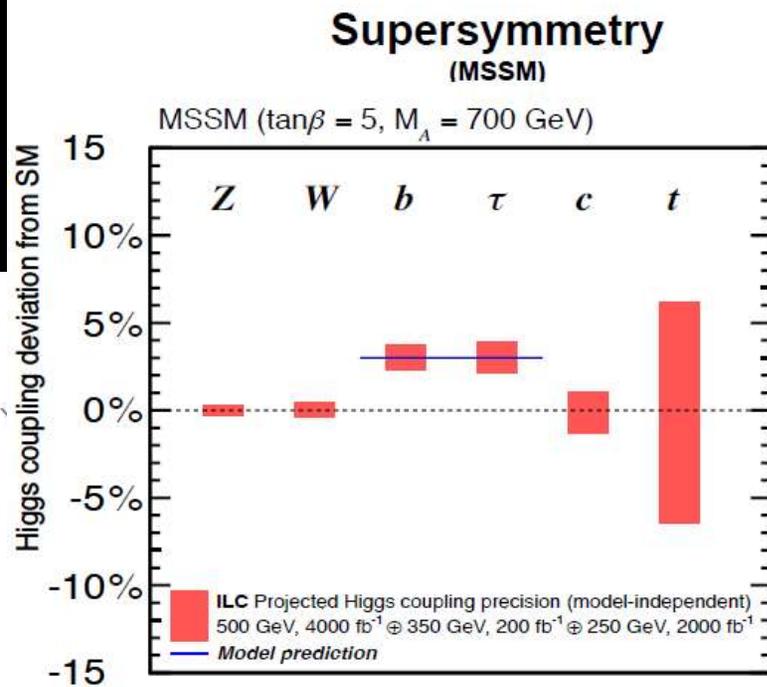
Parameter	Current* 7+8+13 TeV \mathcal{O} (70 fb ⁻¹)	HL-LHC* 14 TeV (3 ab ⁻¹)	FCC-ee Baseline (10 yrs)	ILC Lumi upgrade (20 yrs)	CEPC Baseline (10 yrs)	CLIC Baseline (15 yrs)
σ (HZ)	–	–	0.4%	0.7%	0.5%	1.6%
g_{ZZ}	10%	2–4%	0.15%	0.3%	0.25%	0.8%
g_{WW}	11%	2–5%	0.2%	0.4%	1.6%	0.9%
g_{bb}	24%	5–7%	0.4%	0.7%	0.6%	0.9%
g_{cc}	–	–	0.7%	1.2%	2.3%	1.9%
$g_{\tau\tau}$	15%	5–8%	0.5%	0.9%	1.4%	1.4%
$g_{t\bar{t}}$	16%	6–9%	13%	6.3%	–	4.4%
$g_{\mu\mu}$	–	8%	6.2%	9.2%	17%	7.8%
$g_{e^+e^-}$	–	–	<100%	–	–	–
g_{EE}	–	3–5%	0.8%	1.0%	1.7%	1.4%
$g_{\gamma\gamma}$	10%	2–5%	1.5%	3.4%	4.7%	3.2%
$g_{Z\gamma}$	–	10–12%	(to be determined)			9.1%
Δm_H	200 MeV	50 MeV	11 MeV	15 MeV	5.9 MeV	32 MeV
Γ_H	<26 MeV	5–8%	1.0%	1.8%	2.8%	3.6%
Γ_{inv}	<24%	<6–8%	<0.45%	<0.29%	<0.28%	<0.97%

Courtesy of D. D'Enterria, FCC week 2018, Amsterdam [GeV]

e^+e^- collider potential (2)

❖ ZH: Higgs couplings

■ One order of magnitude better than LHC



ILC Physics WG, '15
arXiv:1506.05992

Recoil Mass [GeV]

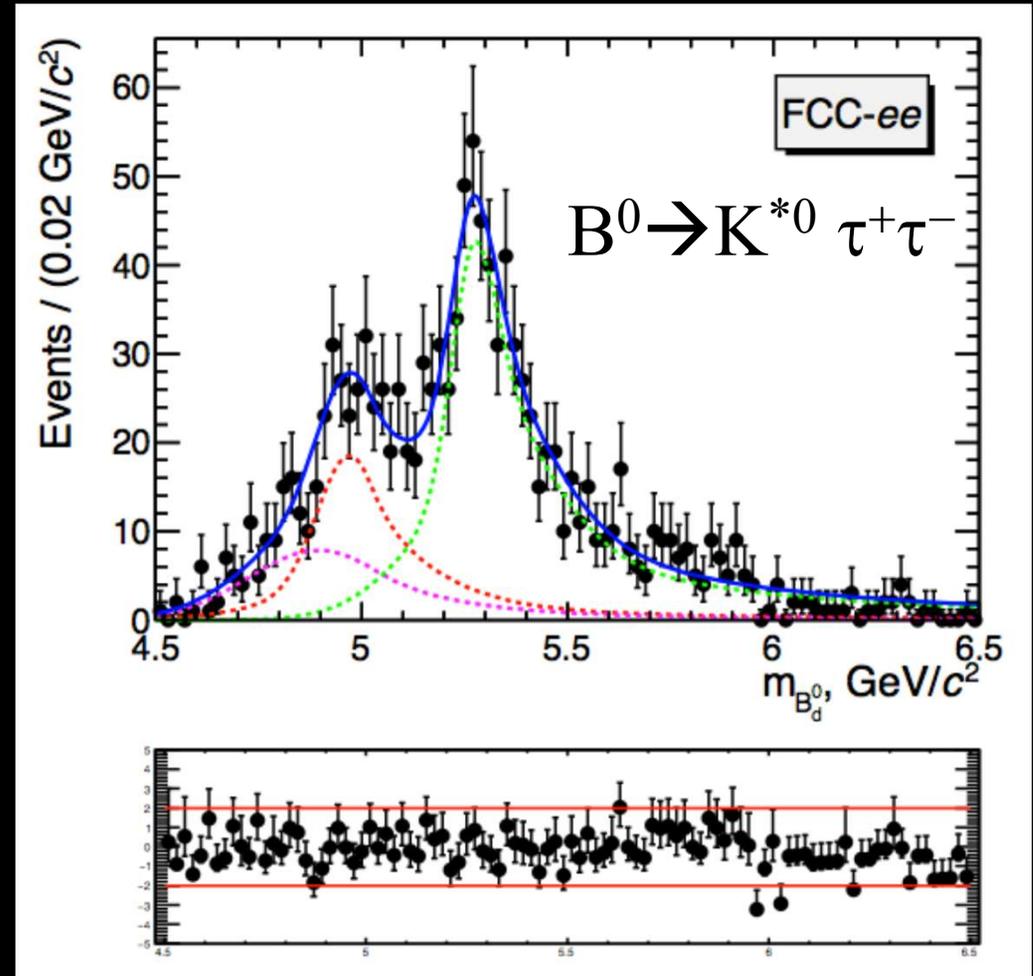
e^+e^- collider potential (3)

❖ Heavy Flavors con 10^{12} b-hadrons

➤ Esempio $B^0 \rightarrow K^{*0} \tau^+ \tau^-$

■ ~1000 eventi

❖ Ancora da studiare....



Machines needing R&D

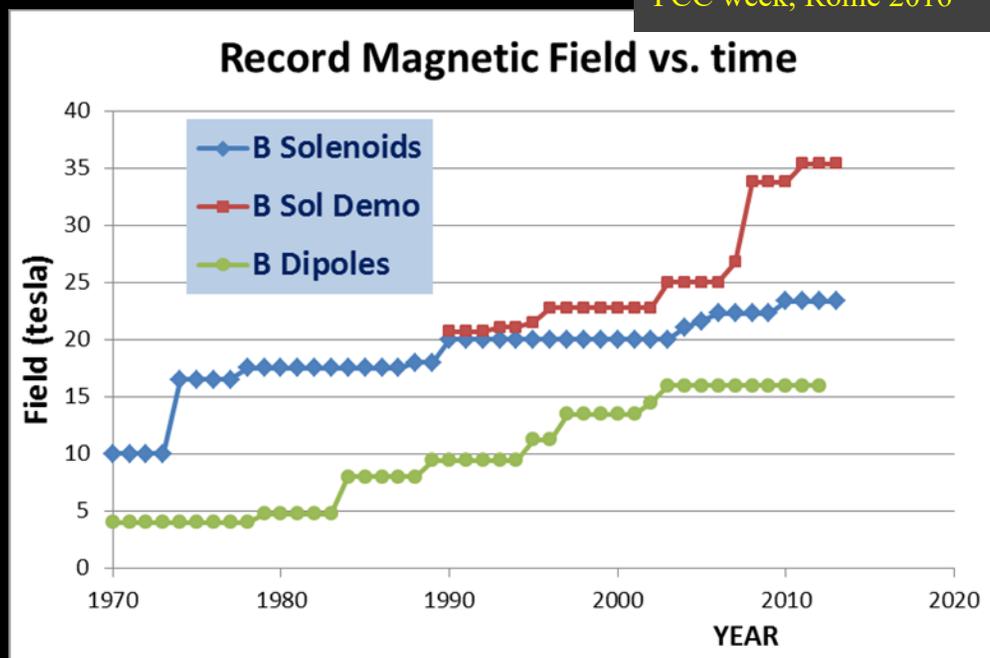
❖ HE-LHC/FCC-hh/SppC:

- Share tunnels with LHC, FCC-ee, CepC

❖ High field Nb₃Sn magnets

- 8 T (LHC) → 16 T
- 20 T with HTS

Courtesy of Gijs de Rijk,
FCC week, Rome 2016



Vedi talk di L. Rossi

Machines needing R&D

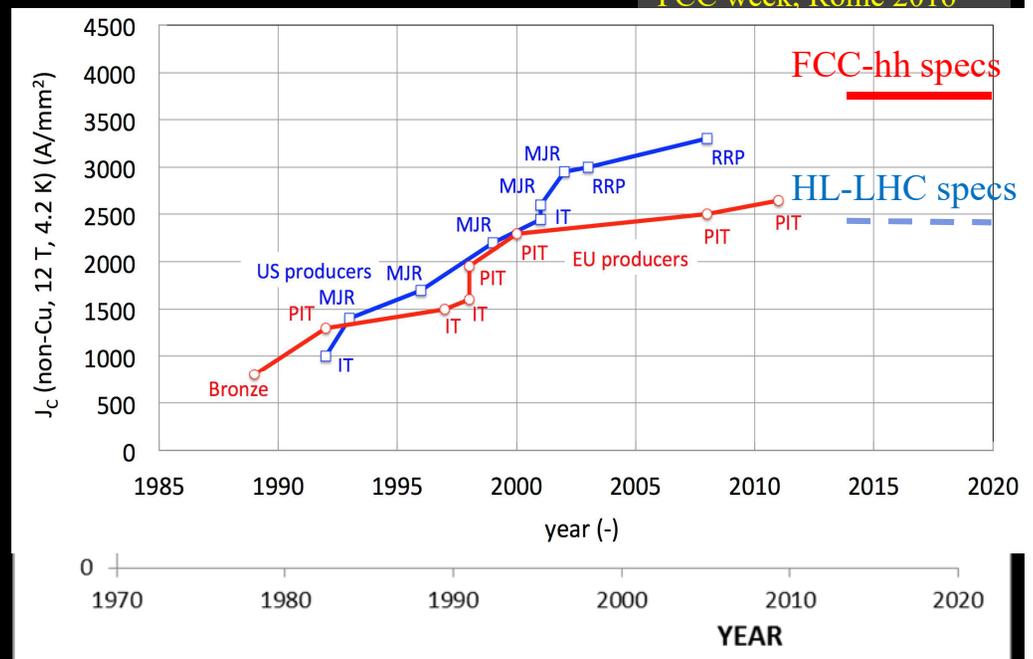
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- 20 T with HTS
- Conductor

Courtesy of Gijs de Rijk,
FCC week, Rome 2016



Vedi talk di L. Rossi

Machines needing R&D

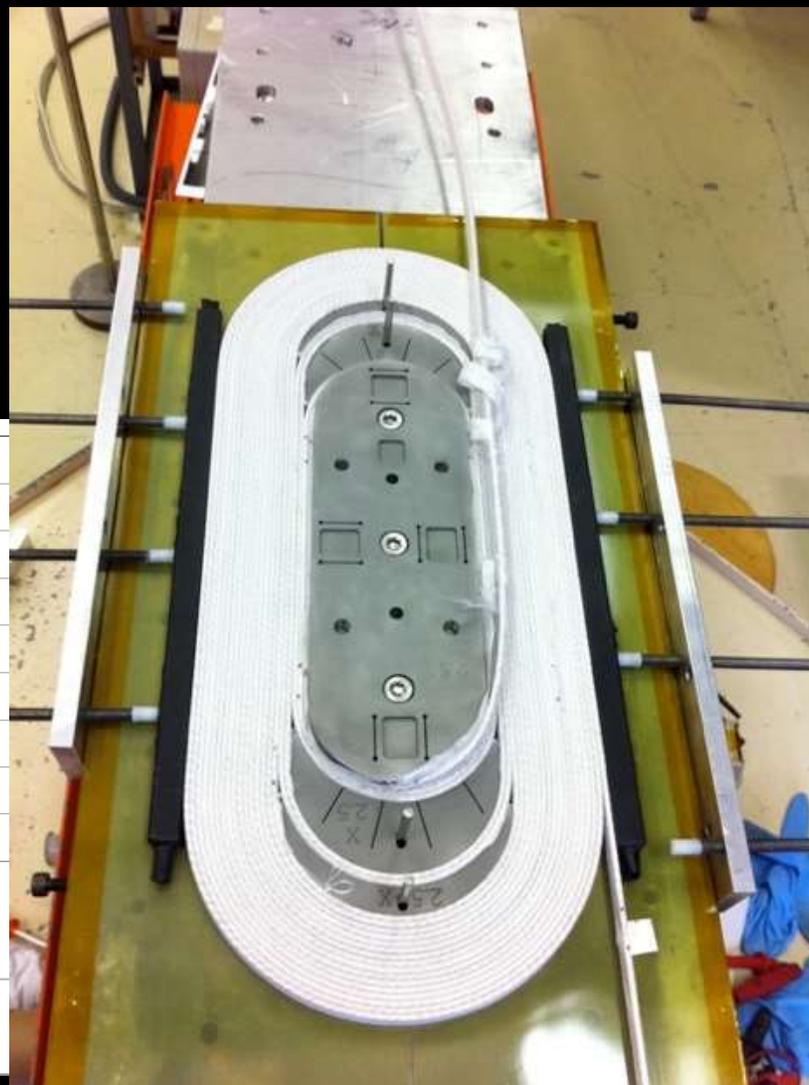
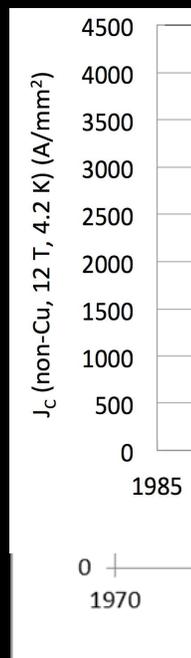
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❖ High field Nb_3Sn magnets

- 8 T (LHC) → 16 T
 - 20 T with HTS
- Conductor
- Complex construction

Vedi talk di L. Rossi



Machines needing R&D

❖ HE-LHC/FCC-hh/SppC:

- Share tunnels with LHC, FCC-ee, CepC

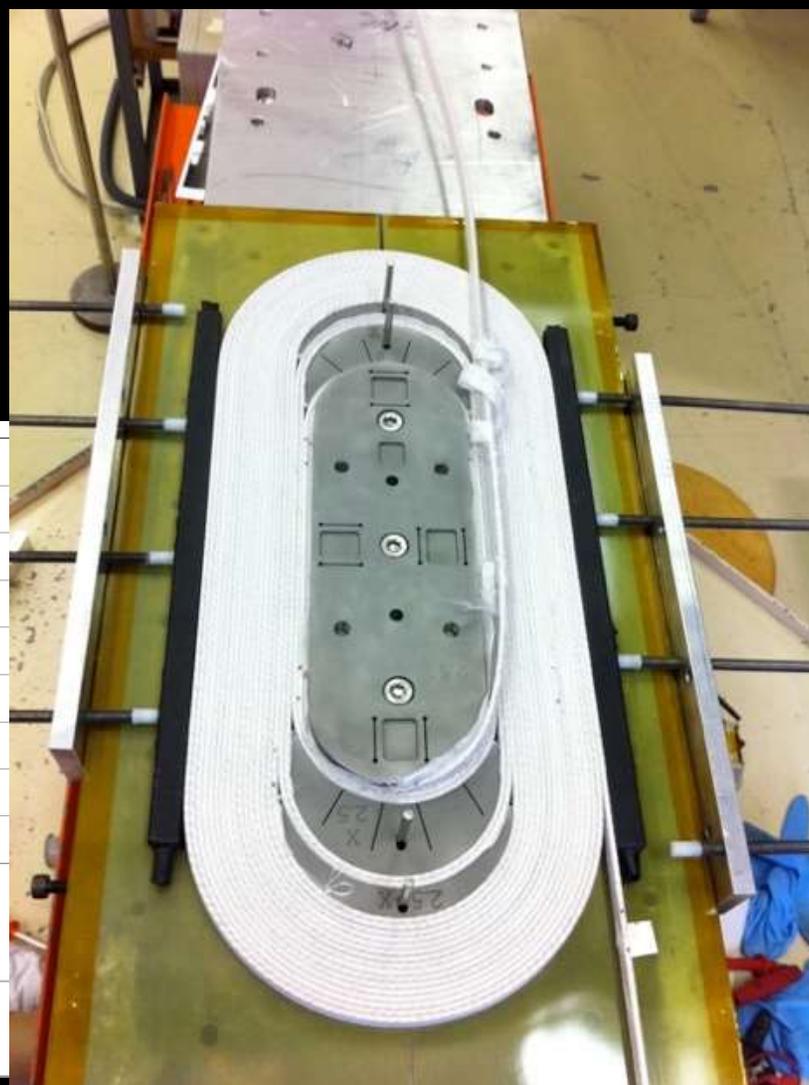
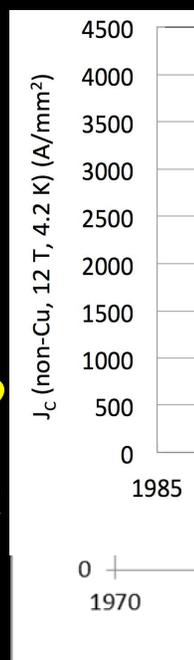
❖ High field Nb_3Sn magnets

- 8 T (LHC) → 16 T
 - 20 T with HTS
- Conductor
- Complex construction

❖ Magneti meno ambiziosi?

- Tempi rapidi vs. E su FCC

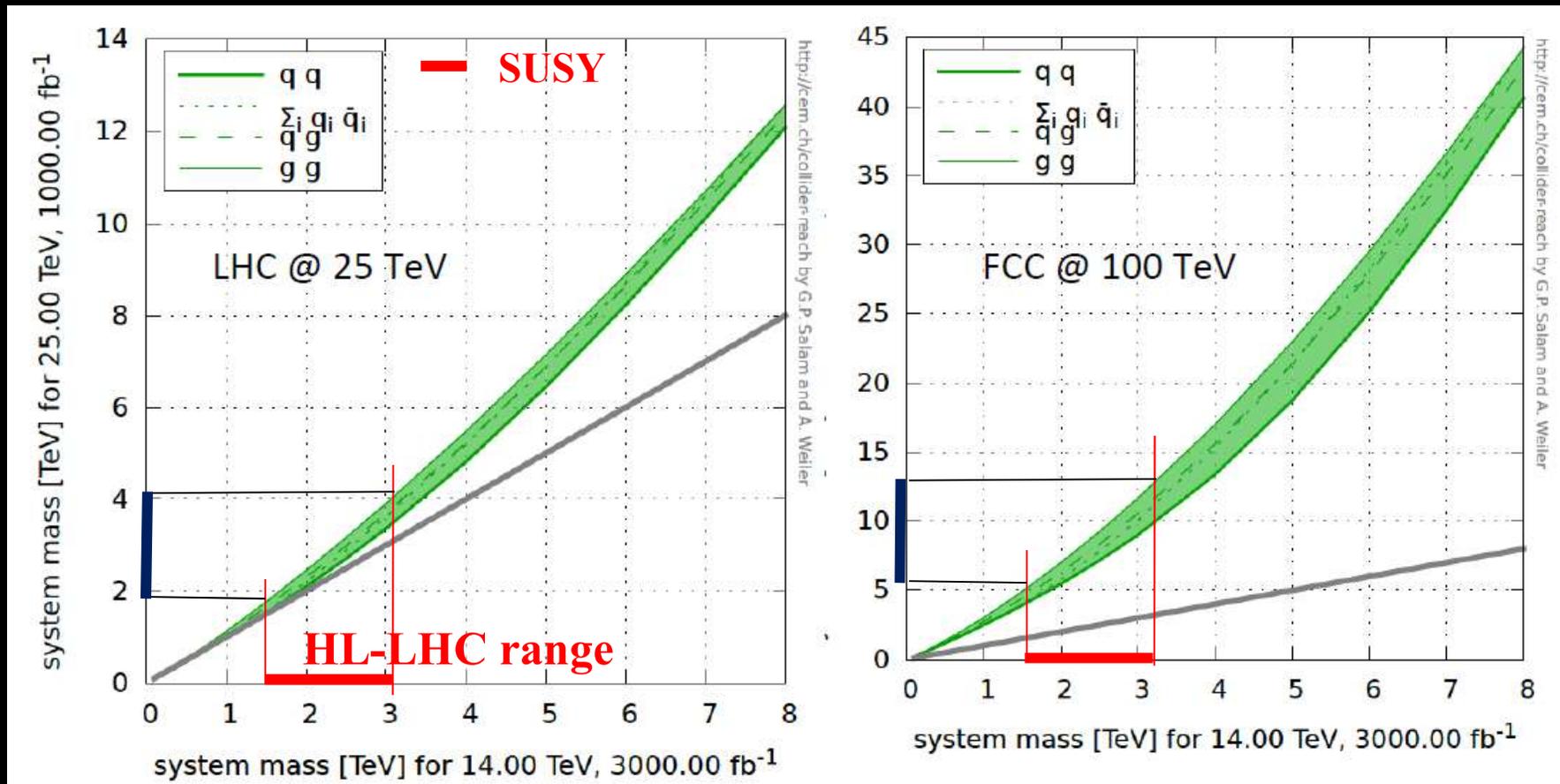
Vedi talk di L. Rossi



pp collider potential (1)

❖ Grande potenziale di esplorazione con $\sqrt{s} = 100$ TeV

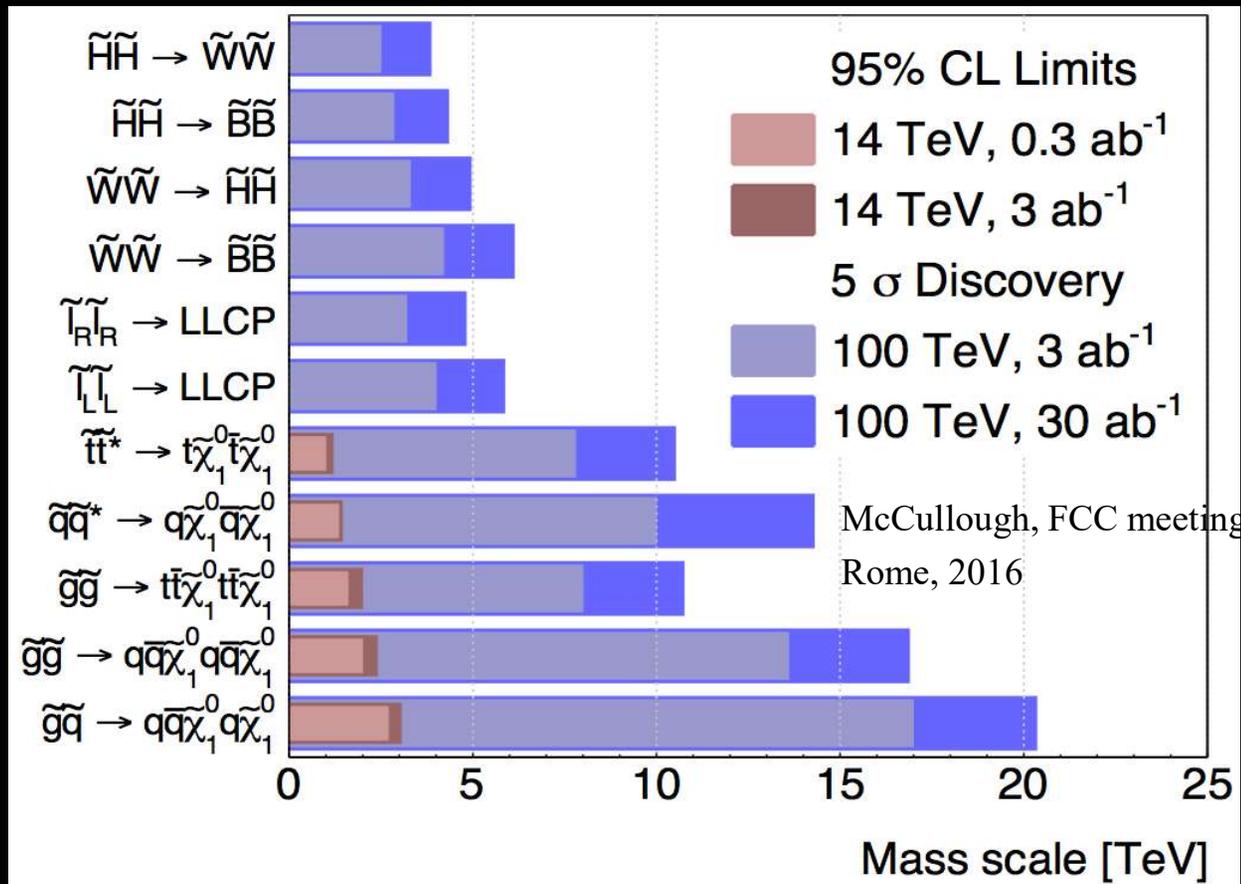
➤ Molto meno con $\sqrt{s} = 25$ TeV, ma utilizza il tunnel di LHC



pp collider potential (1)

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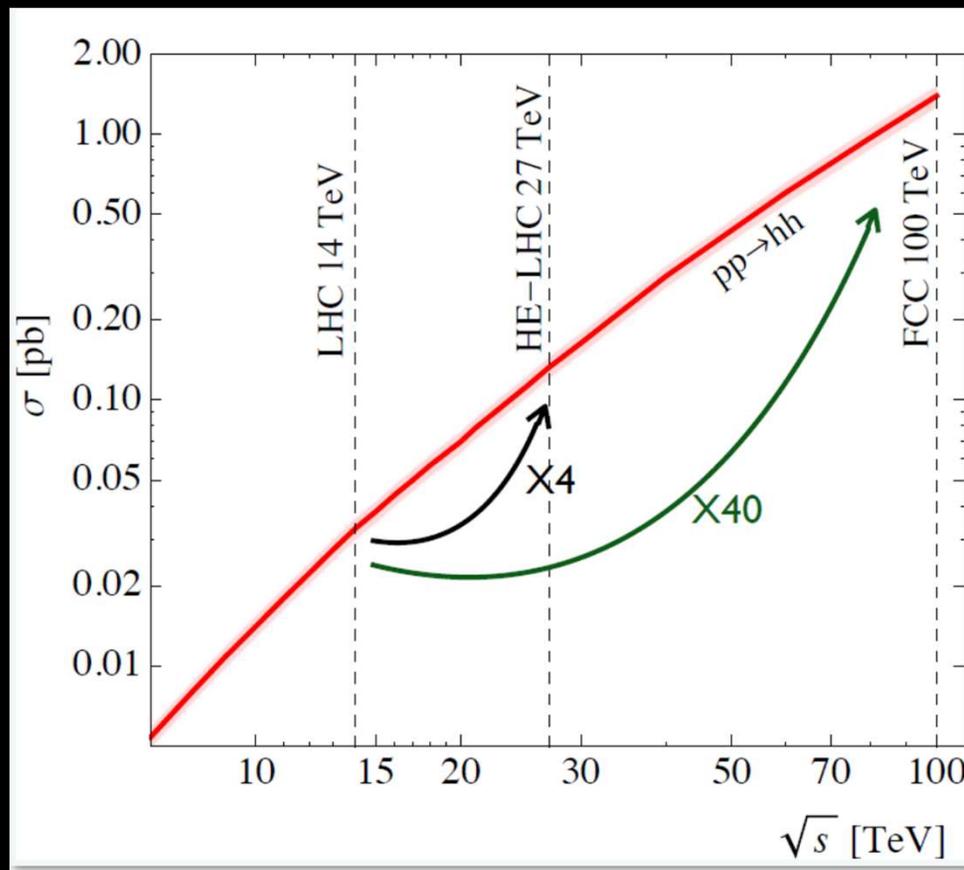


range

pp collider potential (2)

❖ 100 TeV pp per una misura precisa di HH

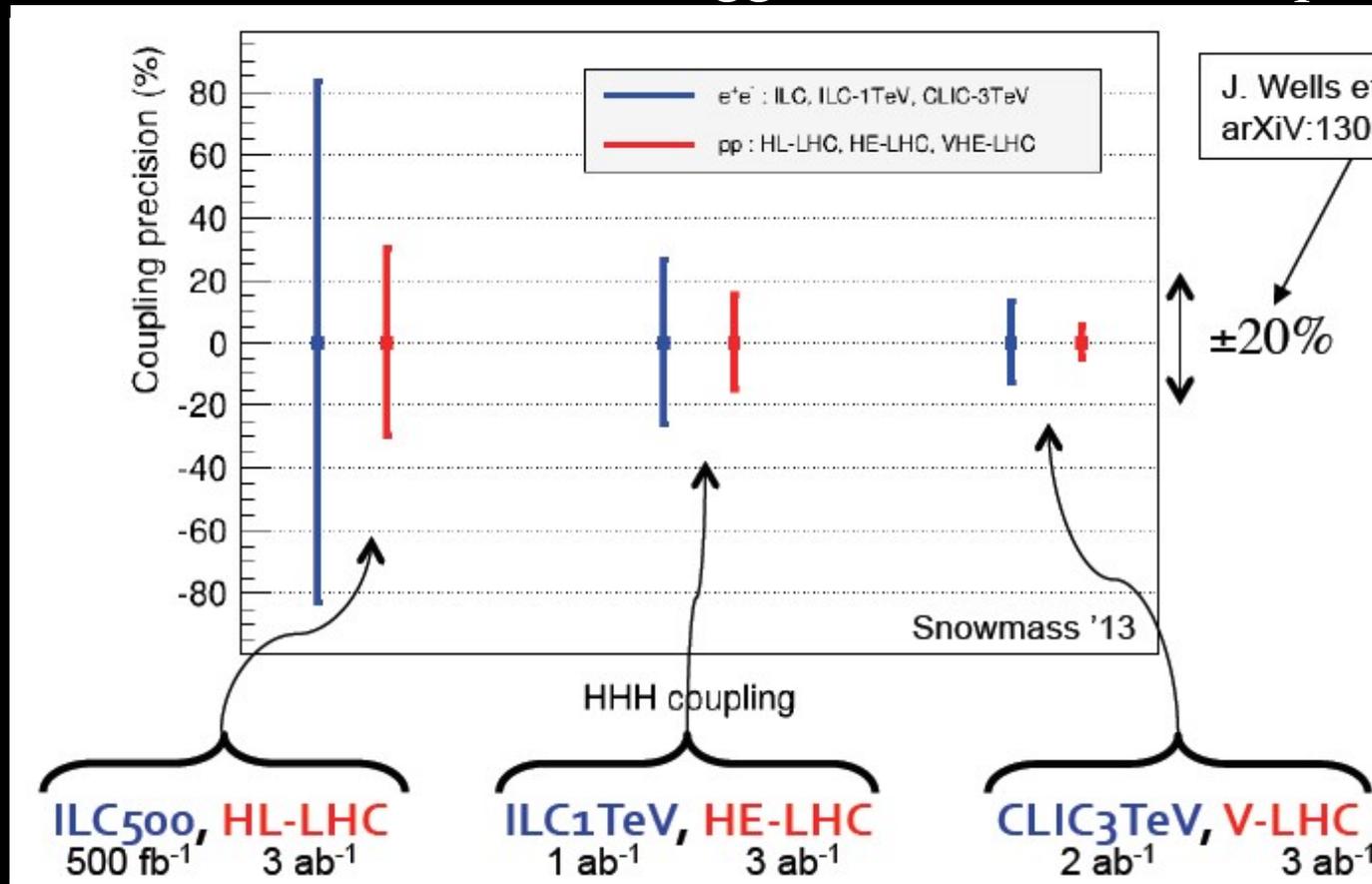
- Si sfrutta x-sec molto maggiore – Nonostante il pile up a 1000



pp collider potential (2)

❖ 100 TeV pp per una misura precisa di HH

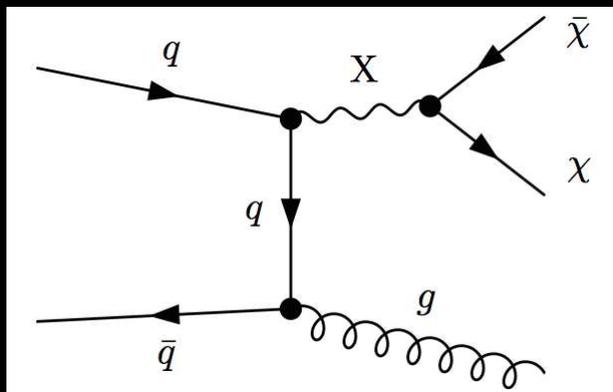
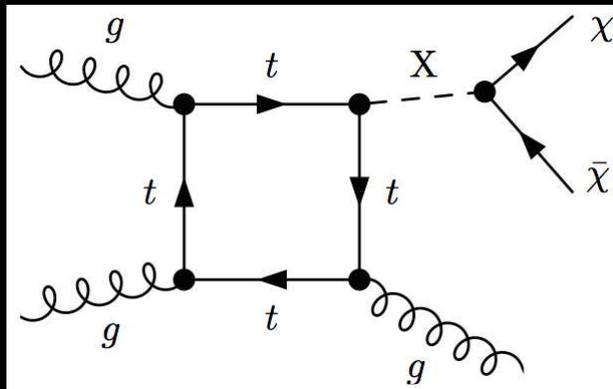
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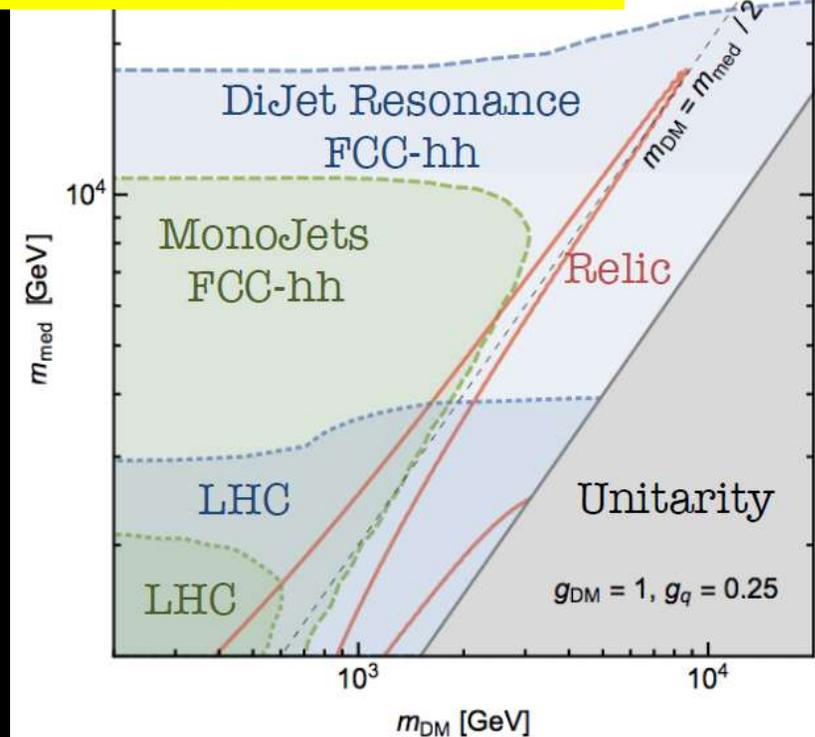
pp collider potential (3)

❖ Dark matter (modelli semplificati)

- 100 TeV pp potrebbe coprire tutto lo spazio dei parametri permesso dalle osservazioni cosmologiche



M. McCullough, FCC week 2016



Muon colliders

❖ Circular $\mu+\mu-$ collider

- 125 GeV \rightarrow 20 TeV
- No beamstrahlung
- Lower power

❖ Due approcci:

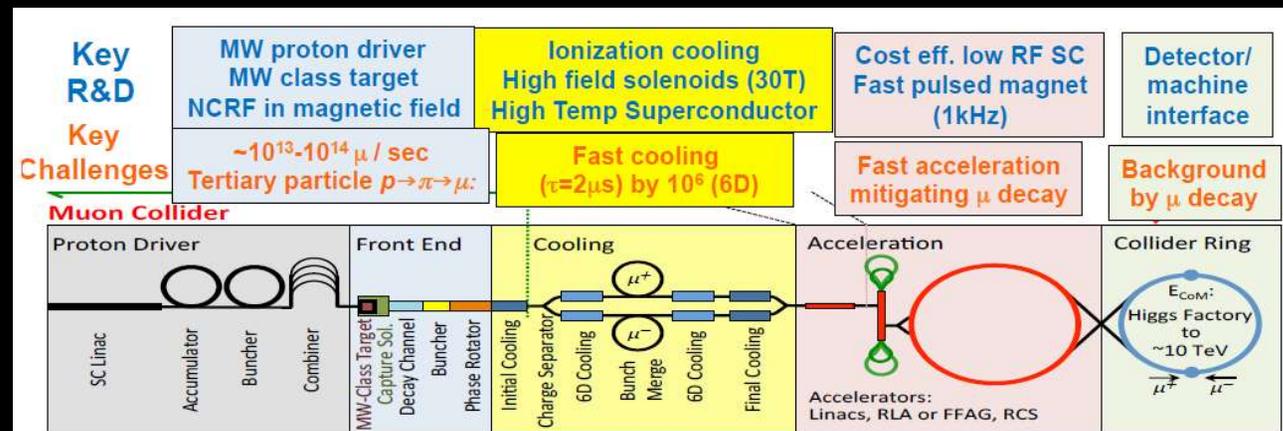
Muon colliders

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- 125 GeV \rightarrow 20 TeV
- No beamstrahlung
- Lower power

❖ Due approcci:

- Proton prod.



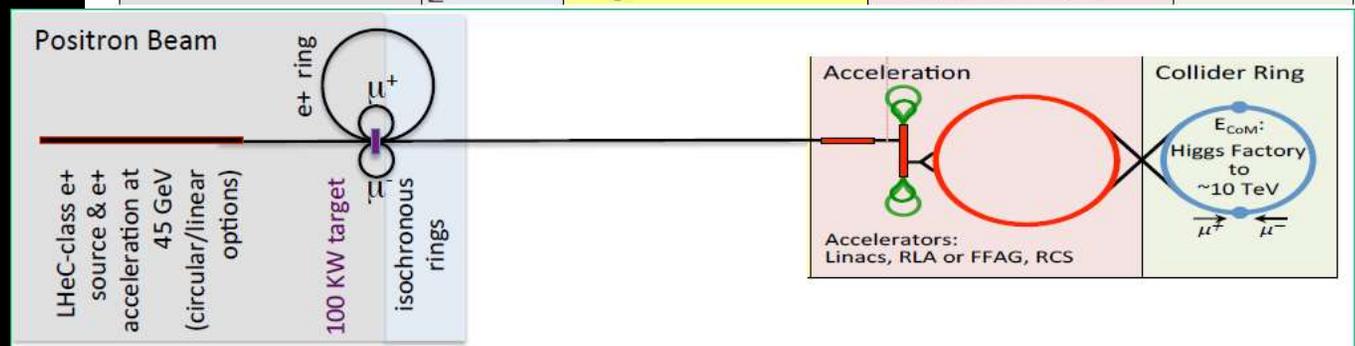
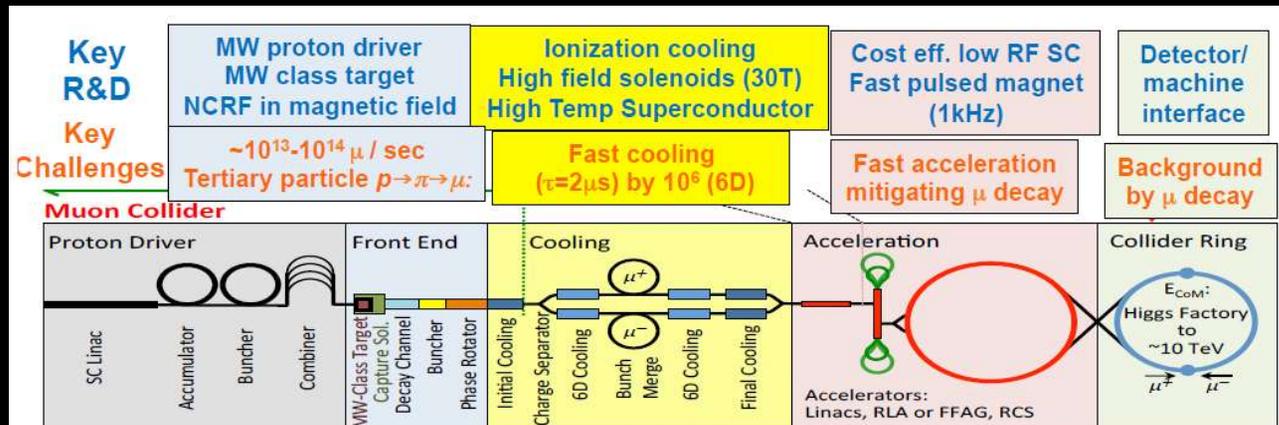
Muon colliders

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- Proton prod.
- Positron prod.



Muon colliders

❖ Circular $\mu^+\mu^-$ collider

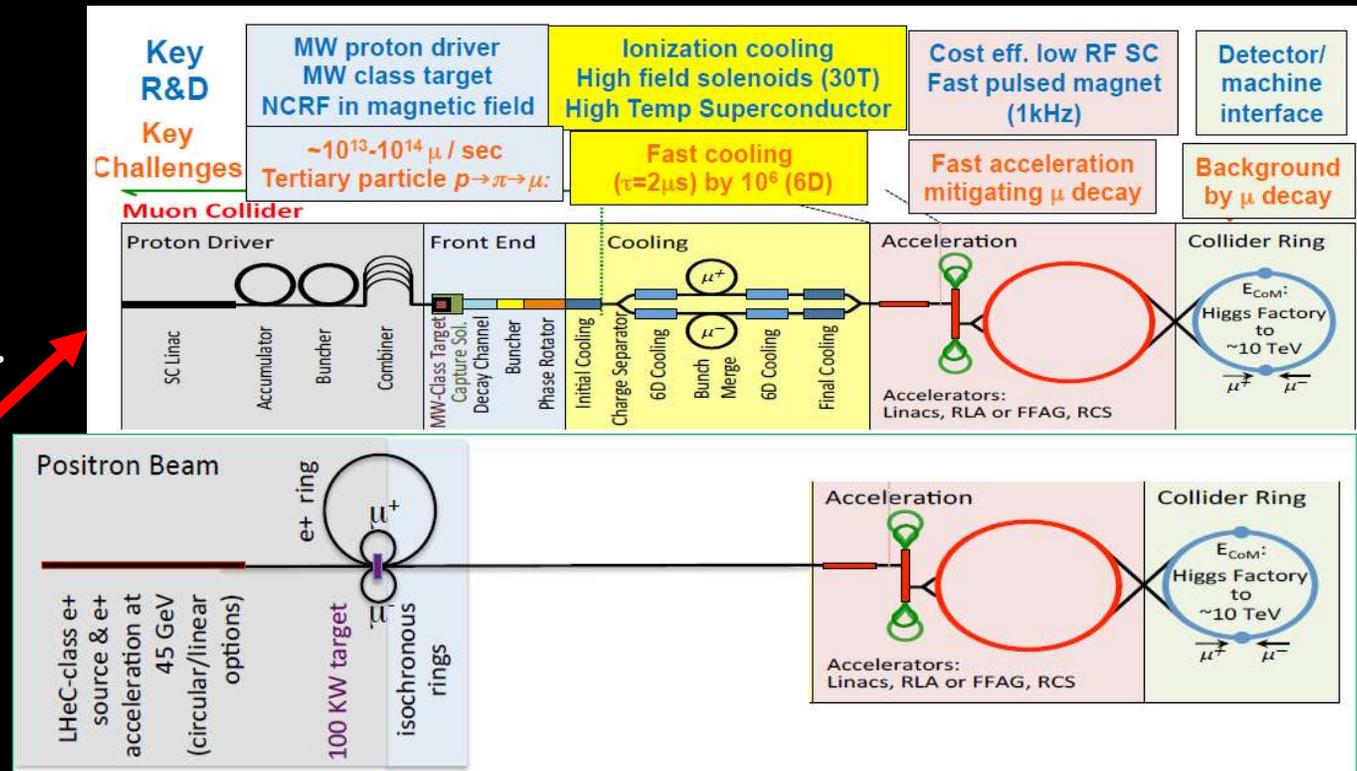
- 125 GeV \rightarrow 20 TeV
- No beamstrahlung
- Lower power

❖ Due approcci:

- Proton prod.
- Positron prod.

❖ Challenges:

- Cooling



Muon colliders

❖ Circular $\mu^+\mu^-$ collider

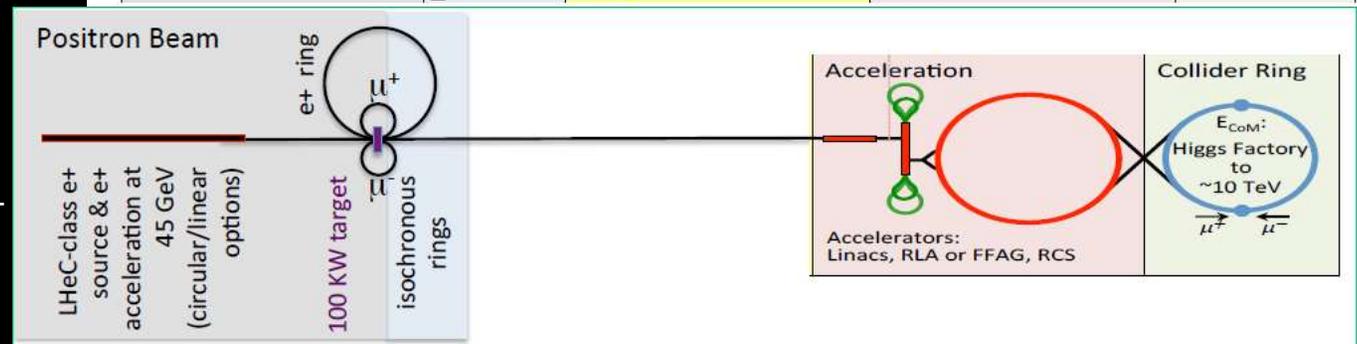
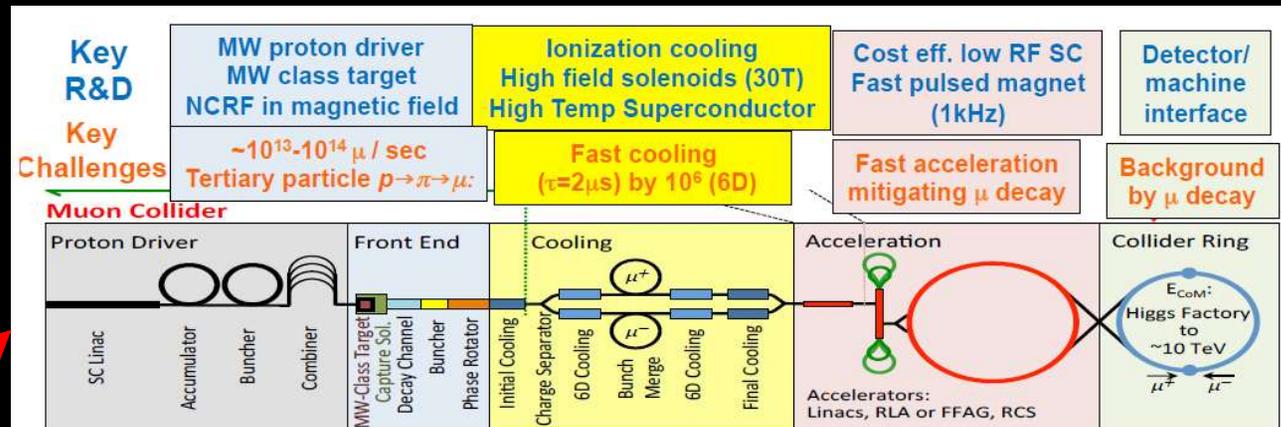
- 125 GeV \rightarrow 20 TeV
- No beamstrahlung
- Lower power

❖ Due approcci:

- Proton prod.
- Positron prod.

❖ Challenges:

- Cooling
- Targhette/#e+



Muon colliders

Vedi talk di M. Biagini

❖ Circular $\mu^+\mu^-$ collider

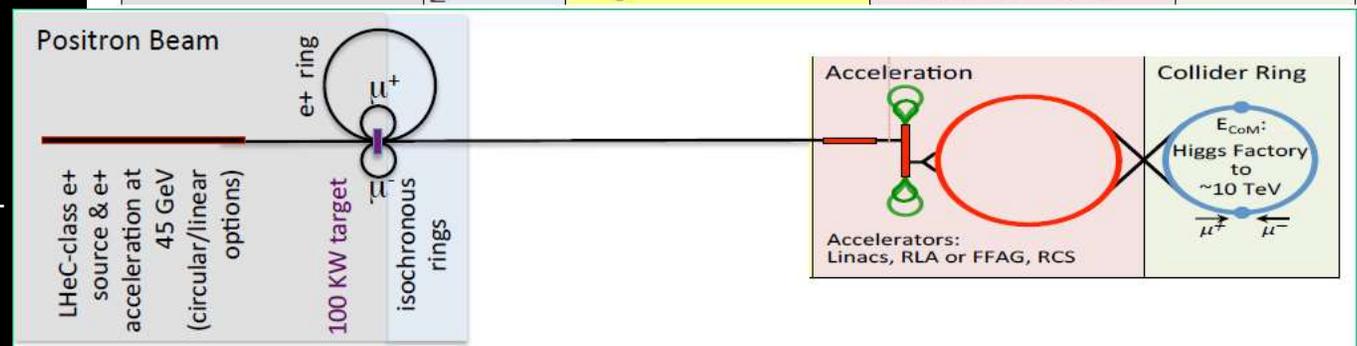
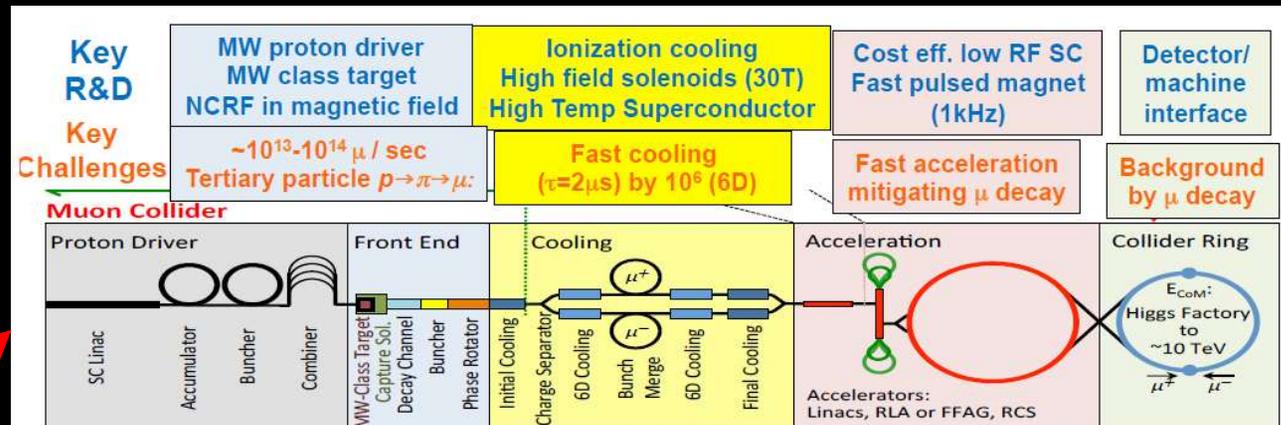
- 125 GeV \rightarrow 20 TeV
- No beamstrahlung
- Lower power

❖ Due approcci:

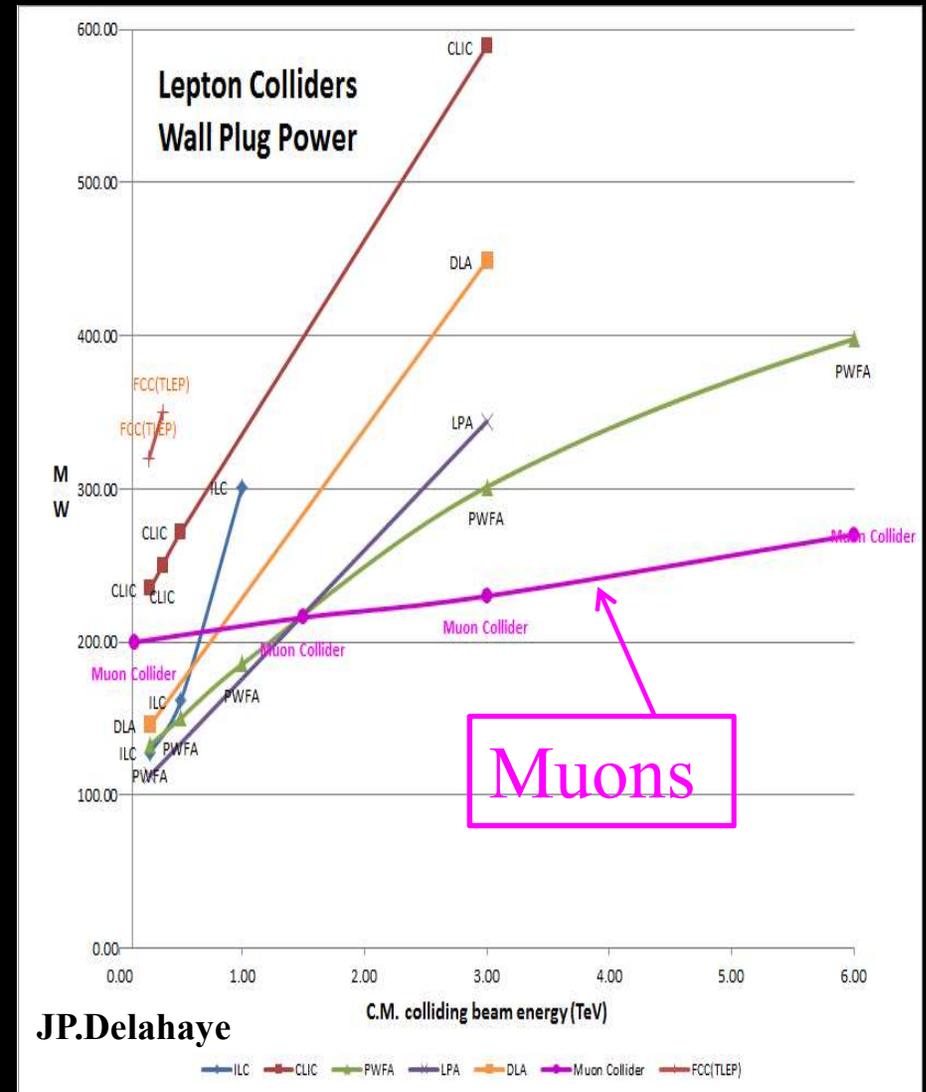
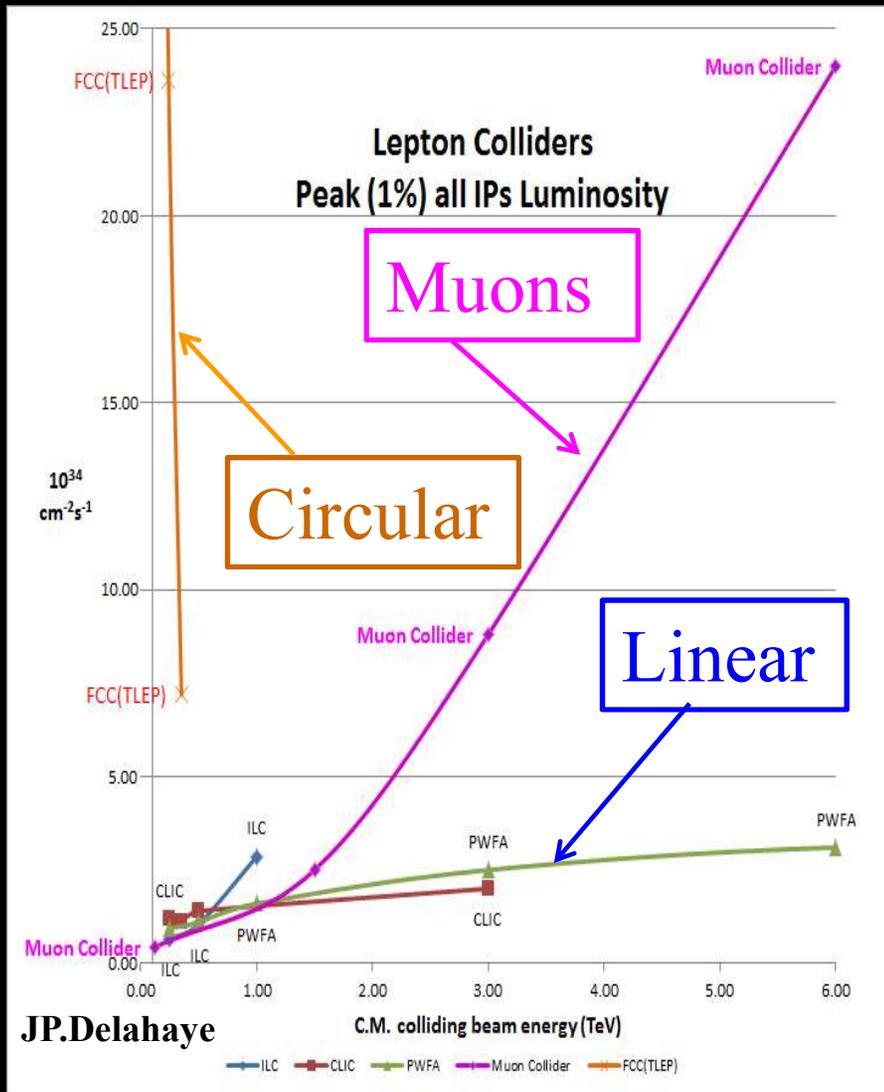
- Proton prod.
- Positron prod.

❖ Challenges:

- Cooling
- Targhette/#e⁺
- Backgrounds

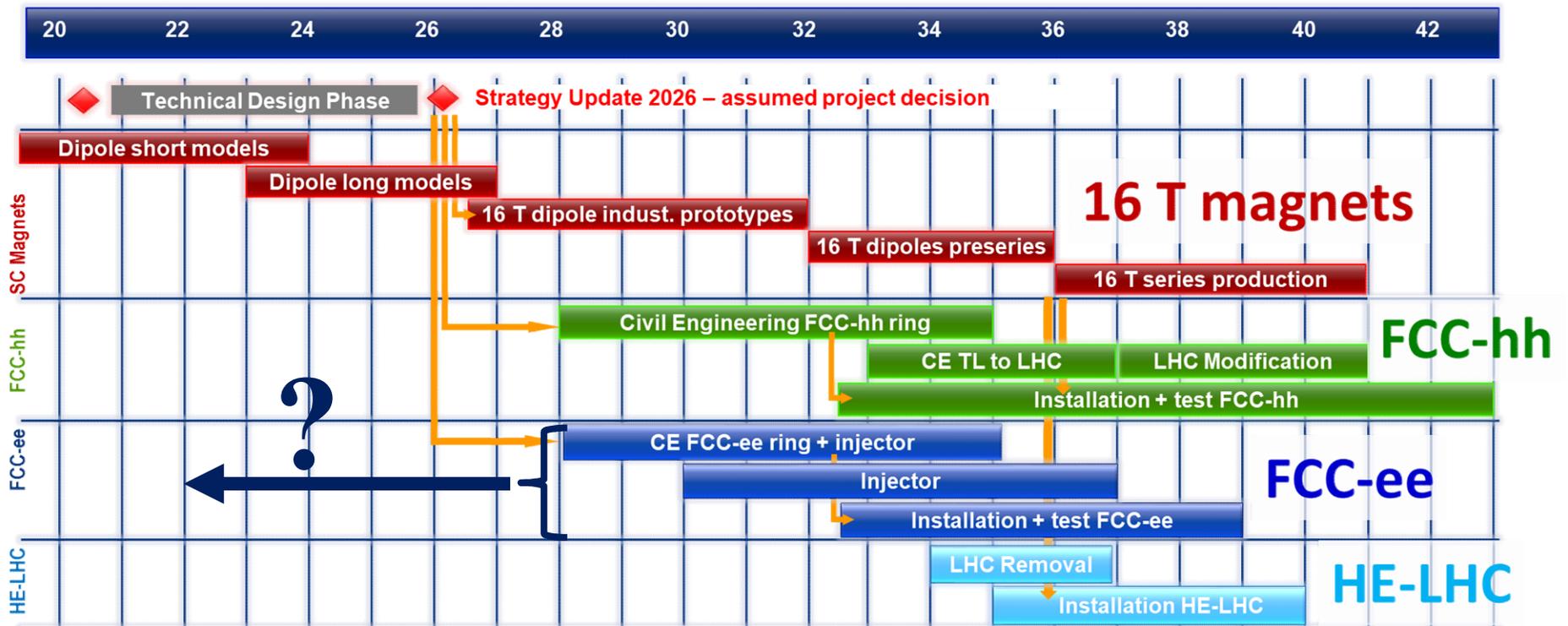


Scaling di machine a leptoni nei TeV



CERN Schedules

❖ FCC proposed schedule



Courtesy of M. Benedikt, FCC week 2018, Amsterdam

China schedule

❖ CepC schedule (ideal = optimistic)



design issues
R&D items
preCDR

design, funding
R&D program
Intl. collaboration
site study

seek approval, site decision
construction during 14th
5- year plan commissioning

Courtesy of Y. Wang, FCC week 2018, Amsterdam

❖ La Cina finanziaria' 1-2 grossi progetti tra ora e il 2030

- Da ora al 2020 selezione di 5-6 progetti per lavoro preparatorio
- Scala costi CepC adeguata – Competizione con altre ~ 50 proposte

Commenti per discussione (1)

❖ Costi HE-LHC/ILC/CLIC380/FCC-ee/CepC ~ comparabili

- FCC-hh molto piu' caro (~ 20-30 B€)
 - Potrebbero scendere in futuro con progressi sulla tecnologia dei magneti
 - FCC-hh con magneti meno ambiziosi e minore energia?

❖ Forti spinte politiche per ILC, ma ...

- La luminosita' non la qualifica come la macchina migliore
- Aumento di energia a 500 GeV/1000 GeV? ... ma quando?
 - Ci sono motivazioni rilevanti per andare a 500 GeV o 1 TeV?

❖ HE-LHC ha un programma di fisica sufficiente?

- Sposta di 30 anni la possibilita' di costruire FCC al CERN
- Nel frattempo pero' i cinesi potrebbero fare CepC

Commenti per discussione (2)

❖ FCC-ee e CepC sono un progetto molto forte

- Costi abbordabili
- Chiaro programma di fisica
- Tecnologia consolidate
- Schedule anticipabile
- Prepara il tunnel per FCC-hh o SppC
- Iniettore di positroni potrebbe servire un futuro muon collider
- TLEP (dentro tunnel di LHC) opzione di backup:
 - ~ 10 volte minore luminosita' basandosi sulla potenza irraggiata

❖ Altre machine innovative sono da perseguire

- Muon coll. modo attraente per avere collider leptonici sopra il TeV